Co-production as an Economically Feasible Pathway to Economy-Wide Electrification

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Abstract

A major proposal to transition the global economy away from fossil fuels is to "electrify everything",(*1*) allowing for low-carbon power production to replace fossil fuel oxidation.(*2*, *3*) Here we conduct a techno-economic analysis of a diverse set of electrification technologies to determine the technical feasibility and economic cost of full-scale electrification. We find that battery-electric vehicles can allow for cost-neutral electrification of transportation; however, neither hydrogen nor CO_2-based e-fuels are economically sustainable. For building-use, electric resistive heating, electric lighting, and heat pumps are sufficiently low-cost to displace fueled processes. Industry is hardest to electrify due to unfavorable thermodynamic limits of carbon-neutral chemistries and because fueled processes operate near their thermodynamic energy minimums.(*4*) Electrification, thus, would add costs when thermochemistry is replaced by single-product electrochemistry. However, industrial electrification could be cost neutral using multi-product pathways, once scale economies allow for sufficient capital expenditure reductions relative to single product chemistry.

Main Text

Despite significant and accelerating decarbonization progress,(*5*) a large gap remains between current greenhouse gas (GHG) emissions reduction pathways and scientifically grounded climate goals such as limiting global average temperatures to 1.5 or 2°C above pre-industrial levels.

Rapidly replacing fossil fuels with emissions-free electricity, the "electrify everything" ethos, is an oft-suggested pathway to meeting climate targets.(*1–3*) Levelized costs of renewable energy generation and storage considering both capital and operating expenditures (CapEx and OpEx, respectively) are low and falling,(*6*) but significant hurdles persist. Specifically, it remains unclear whether electricity and electrified CapEx are cost-competitive or even neutral with fossil fuels. Here, we perform an economy-wide techno-economic analysis of a host of suggested electrification pathways. We show here that electricity and electrified CapEx are typically more expensive than fossil fuels and fueled CapEx, respectively. Moreover, while the sum of CapEx and OpEx is smaller for renewables, the ratio of CapEx to OpEx for fuel-free electricity is larger, exacerbating the financing challenge.(*7*)

The most challenging sector to electrify is industry, where the difference in price per unit energy between fossil fuel and electricity is typically >10x. We find here that by introducing co-generation and process intensification into systems where it does not currently exist, costs of electrification fall significantly and could indeed be accomplished within humanity's apparent willingness to pay for decarbonization. Meanwhile, industrial electrification without co-production requires significantly steeper energy price cost and CapEx reductions.

We offer a framework to identify solutions that are economically cost-neutral and could speed up climate mitigation efforts. In particular, we show that electrifying transportation can be cost neutral using existing technologies (Figure 1), with a similar conclusion holding for building electrification (Figure 2).

For industry, we begin with the realization that electrified single product reactions that replace thermal reactions typically increase cost (Figures 3-4), while electrified (even electrochemical) cogeneration schemes which replace fueled single product schemes may be economical. However, this electrification must be lower cost than a fueled cogeneration pathway, lest it be unseated by a fueled technology (Figures 5-6).

Because CapEx is a substantial fraction of levelized costs, and electrified CapEx is so high relative to thermochemical CapEx, 24-hour production is typically much lower cost than intermittent production, even if intermittent energy is free (see Supplementary Figures 8-12). That points to the importance of significant reductions in CapEx, rather than solely increasing efficiency of electrified systems, as a necessary condition to fully electrify the economy (Figure 8, Figure 10).

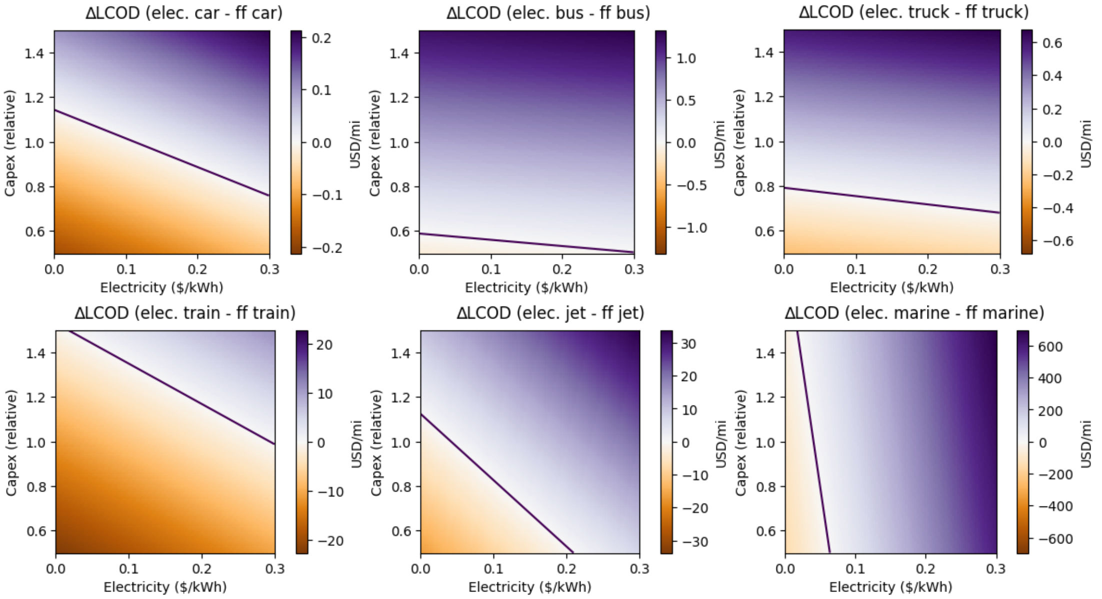
Modeling Electrification

Because this analysis looks at nascent technologies to determine if there is a cost neutral or advantaged path to electrify everything, we use generous assumptions to ensure no feasible route is discounted, including allowing electrical CapEx to be 50% cheaper than conventional estimation methods and allowing electricity to be 10x cheaper than the lowest U.S. prices today. We then use levelized cost of transportation, heating/cooling, and commodity products to determine whether electrification could be lower cost than the conventional (fueled) equivalents. We validate our cost model by showing that major historical electrification events always had lower levelized costs over their lifetime than the technologies they supplanted under our assumptions (see Methods).

Transportation

Transportation accounts for around 15% of total GHGs, with only ~2% of emissions associated with electricity generation.(*8*) Figure 1 shows the electricity price required for full electrification of each of the major transportation categories – ship, train, plane, truck, car, and bus to reach levelized-cost parity with the fueled version within our generous, allowable electricity prices and CapEx assumptions. For transportation, electrification can reduce energy use because electric motors are more efficient than fueled engines,(*9*) but this has a diminished effect on total cost as it increases the ratio of CapEx to fuel cost.

Figure 1. Difference in Levelized Annual Cost of Distance (ΔLCOD, US$/mi), for various electrified (elec) transit modes compared to their fossil fueled (ff) equivalents. Differences were computed using a discount rate of 15%.

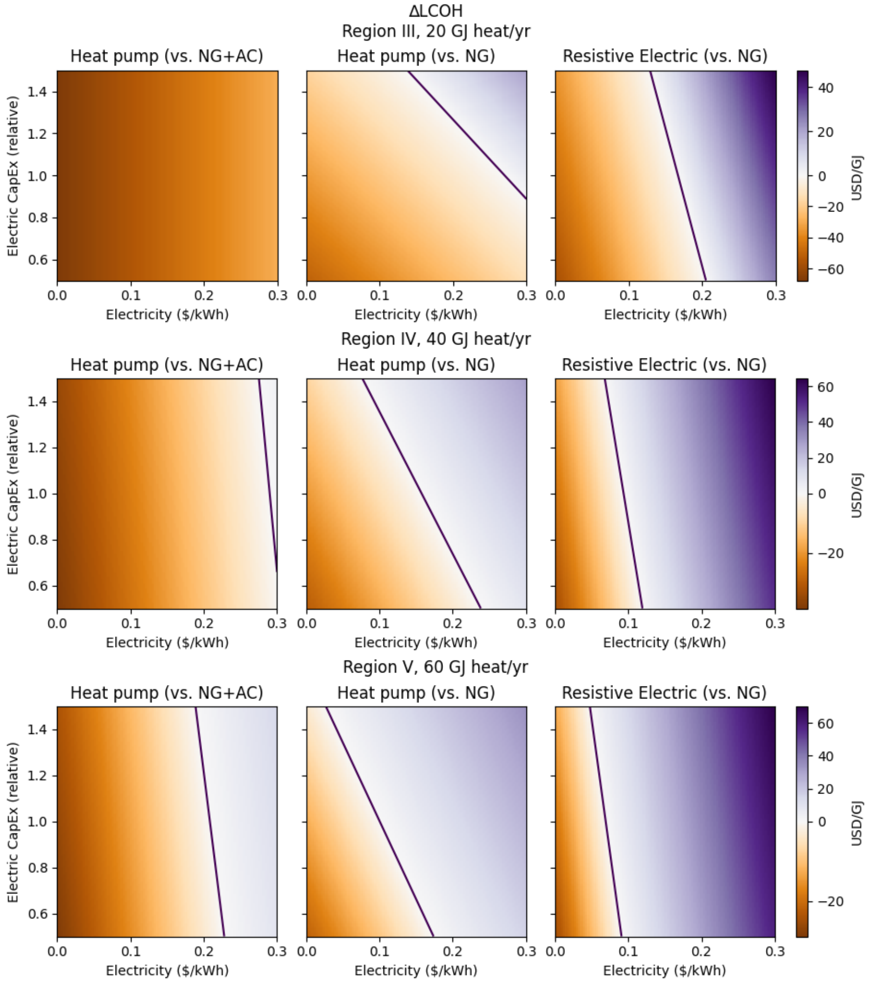


This is the case for vehicles with extremely high manufacturing costs relative to their utilization (planes, cars). In these cases, a significant reduction in CapEx compared to today, but not compared to our allowable assumptions is required for electrification to be competitive with fossil fueled alternatives. This is why recent studies of fleet vehicles show significant cost reductions for owners– utilization is high so operating expenditures (the recurring cost of operating the equipment, like gasoline and maintenance for a car or labor and raw materials for a chemical plant; OpEx) is the dominant cost – while personal vehicles are still more expensive for owners compared to fueled vehicles (utilization is low so CapEx is the dominant cost).(*10*, *11*) However, as electrified CapEx falls, vehicles with low utilization become fully cost parity even at modern energy prices. By contrast, vehicles with high utilization (marine shipping) are relatively insensitive to changes in electrified CapEx. We also performed an e-fuels-OpEx-only analysis, which results in a lower levelized annual cost of distance (LCOD) than a full analysis, but we found that OpEx alone, even with our generous assumptions, is unable to be lower cost than fuel (see Supplemental Information).

Buildings

Building energy use is already highly electrified, with 60% of the sector's GHG emissions due to electricity production. Fuel use makes up the majority of remaining emissions, with space heating being the dominant use of fuel.(*12*) Generally, the high cost of distributed fuel in buildings allows electrified systems to compete with fueled systems. Heat pumps deployed widely for heating and cooling will save energy over gas and electric systems, especially in warmer climates where seasonal average efficiency is higher. When compared to other options for heating plus cooling (e.g. an air conditioner plus natural gas or fuel oil heating), heat pumps are often the lower cost solution, even in cold climates, particularly when fossil fuel costs are high relative to electricity:

Figure 2. Levelized Cost of Heating (ΔLCOH, US$/GJ) for heat pumps and resistive electric furnaces. Differences were computed using a discount rate of 15%.



For cooking, the CapEx of electric stoves is within the statistical error of gas stoves, allowing for the electrification of cooking without additional expenses. That holds for resistive heating as well as for modern electric induction.

However, the comparison only holds in high-income countries, where electrification is compared to gas; for low-income countries, electrified stoves are still among the least affordable options because they compete directly with open, biomass burning fires where fuel prices are paid almost exclusively in women’s labor. Electrified cookstoves are, thus, an important development intervention, oft wholly dependent on aid. Substantial economic development would need to occur before electrified cooking becomes economically affordable under these circumstances.(*13*, *14*)

Industry

Industrial emissions associated with electricity generation, use of fossil fuel heat, and process-related CO_2-emissions add up to ~1/3 of total global GHG emissions. High-temperature process heat and process emissions account for 65% of all industry-related GHG emissions.(*4*) Low-temperature process heat (<150 °C) can be electrified with high efficiency using heat pumps, although energy prices are substantially different than for buildings and transportation; direct electrification would likely be more cost-effective for medium- and high-temperature process heat due to the low efficiency of heat pumps for producing high-temperature heat.

Process-related emissions arise due to the use of carbon-containing reagents, typically for reduction and/or deoxygenation, but also in the form of metal carbonates calcined to their corresponding metal oxides. These carbon-containing reagents are used in thermochemical reactions, as in the carbothermal reduction of iron and silicon or the calcination of limestone, and electrochemical reduction, notably as a consumable anode in aluminum electrolysis. Full decarbonization ultimately requires electrification of fossil fuel heat *and* replacement of carbon reagents with other reducing agents (either regenerable or whose oxidation yields valuable co-products), development of oxygen-producing (inert) anodes, or development of novel processes.

We analyzed a subset of technologies (cement, steel, aluminum, hydrogen, ammonia, and methanol) that represent a diverse cross-section of industry, with difficult-to-abate process emissions, to determine the capacity for electrification and decarbonization.

Electrochemical Decarbonization

Given the recent efforts to replace thermal production of commodity chemicals with electrochemical processes,(*15–20*) we analyzed electrochemistry (the use of voltage to drive chemistry) using a levelized cost approach (methods, equation 1). Given the pathfinding nature of this work, we used very generous assumptions for electrochemistry to make sure that we did not miss any possibilities to electrify industry. These included allowing energy consumption to be at the thermodynamic minimum (a practical impossibility) and electricity prices to be ~10% of typical industry prices. When analyzing water electrolysis, for example, our estimated CapEx is the same as nascent companies which purport to have extraordinarily low-cost electrolyzers (our analysis is $5,265/T versus $4,850/T for an example company which is also ~50% lower cost than current commercially available Western electrolyzer prices). Because of these assumptions, our ultimate levelized cost of hydrogen is estimated to be well below existing published data. For example, previously published estimates have been $5-6/kg at $0.07/kWh;(*21*) our estimate is $4-4.5/kg. Our analysis allows for costs as low as $0.70/kg with our lowest electrified CapEx and electricity assumptions (50%, $0.01/kWh).

For ammonia and all products, we conservatively assumed that direct synthesis of the product is possible from the reactants with current densities typical of industrial processes in a single electrochemical reactor which, to our knowledge, are an order of magnitude higher than any demonstrated nitrogen reduction current densities.(*16*, *22*) Higher current densities are possible for nitrate reduction to produce ammonia,(*23*) though nitrate source, purity concerns, and unfavorable thermodynamics would need to be addressed to bring this technology to market. Our analysis also suggests that if low-cost hydrogen were available from water-splitting, it would be cheapest for ammonia to be produced using that hydrogen in an electrified conventional Haber-Bosch process.

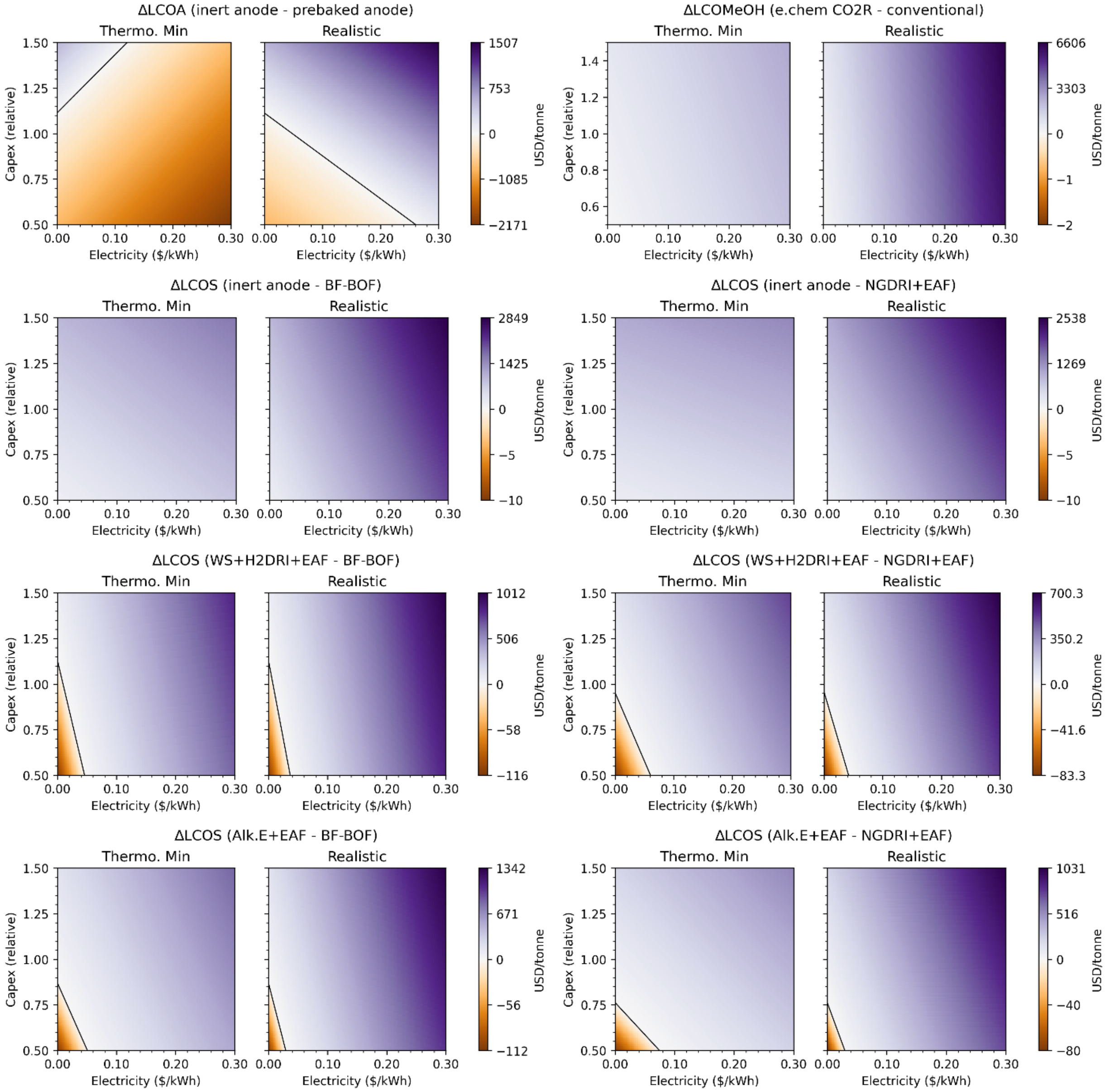
For aluminum, the baseline estimated CapEx may be an overestimate, driven by similarity of its operational parameters to conventional aluminum production despite not requiring CapEx for anode fabrication. However, allowing for a 50% reduction in CapEx ensures generous assumptions.(*24*, *25*)

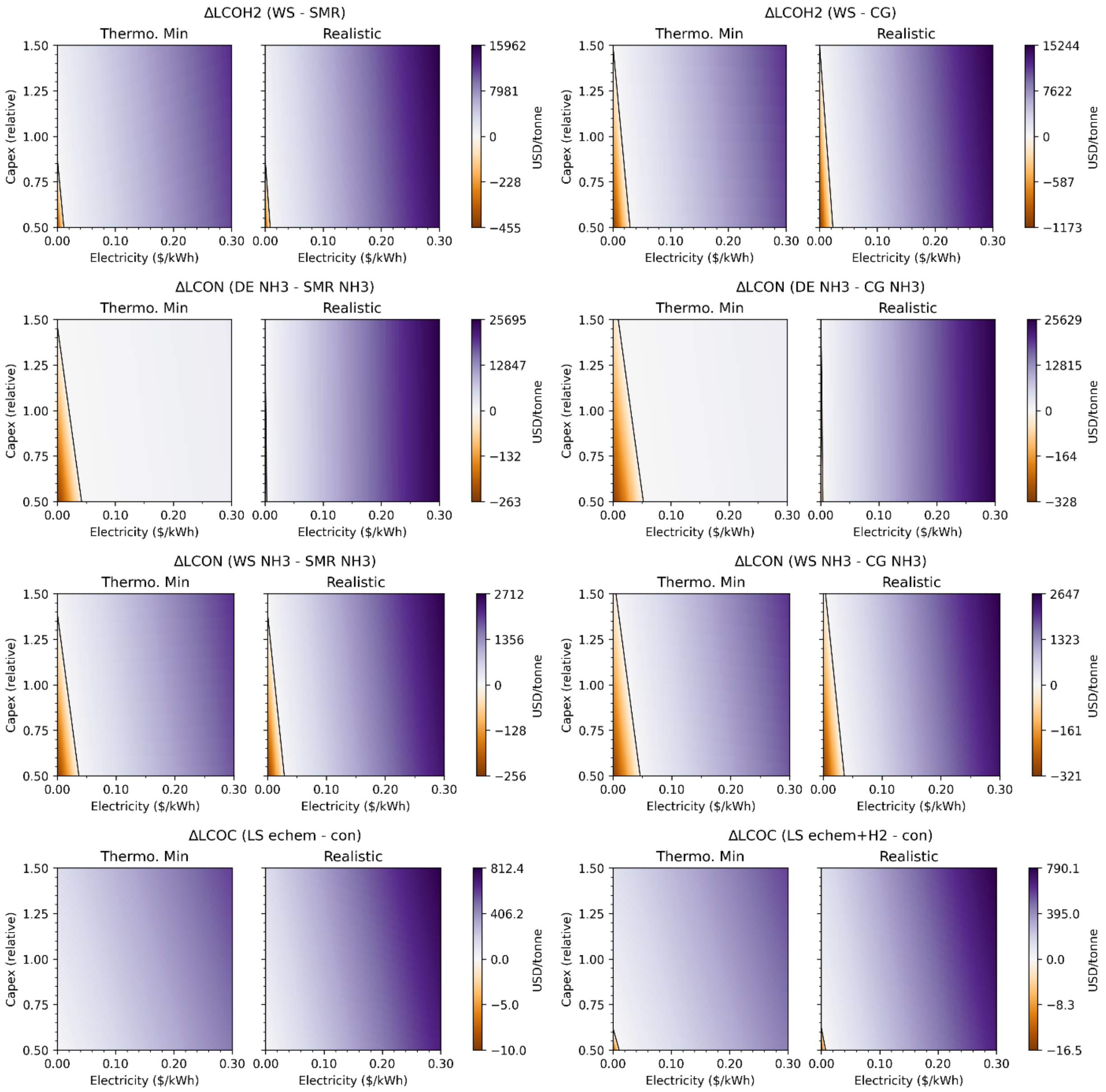
For iron, because the estimated CapEx for electrochemical processes decreases with temperature,(*26*) lower-temperature electrochemical routes (alkaline electrodeposition + EAF steelmaking) break even with conventional processes at ultra-low electricity prices and low CapEx, while higher-temperature electrochemical routes are never cost-competitive. To address the possibility that front-end processing CapEx for molten oxide electrolysis (which we estimate at 70% of total CapEx) is overestimated we allow wide CapEx error bars. Still, molten oxide electrolysis (MOE) was not found to be economic.(*24*)

While this analysis initially suggests that steel can be electrified with H_2 provided by water electrolysis for DRI iron-making, the cheapest source of H_2 under almost all scenarios is itself not electrified. Therefore, actors seeking to minimize the total levelized cost of steel would utilize SMR and CG H_2 for ironmaking with hydrogen (refer to Figure 3).

Figure 3. Difference in Levelized Cost of Aluminum (ΔLCOA), Methanol (ΔLCOMeOH), Steel (ΔLCOS), Hydrogen (ΔLCOH2), Ammonia (ΔLCON), and Cement (ΔLCOC) for various decarbonized electrochemical processes compared to conventional processes, using thermodynamic minimum (TM) and realistic (R) electricity requirements. N.B. cement production from limestone is not fully decarbonized, as there are still process emissions associated with the decomposition of limestone. BF-BOF = blast furnace-basic oxide furnace; NGDRI+EAF = NG DRI and EAF steelmaking; WS+H2DRI = water-splitting + H2 DRI;

WS = water-splitting; SMR = steam methane reforming; CG = coal gasification; DE = direct electrolysis; LS = limestone.

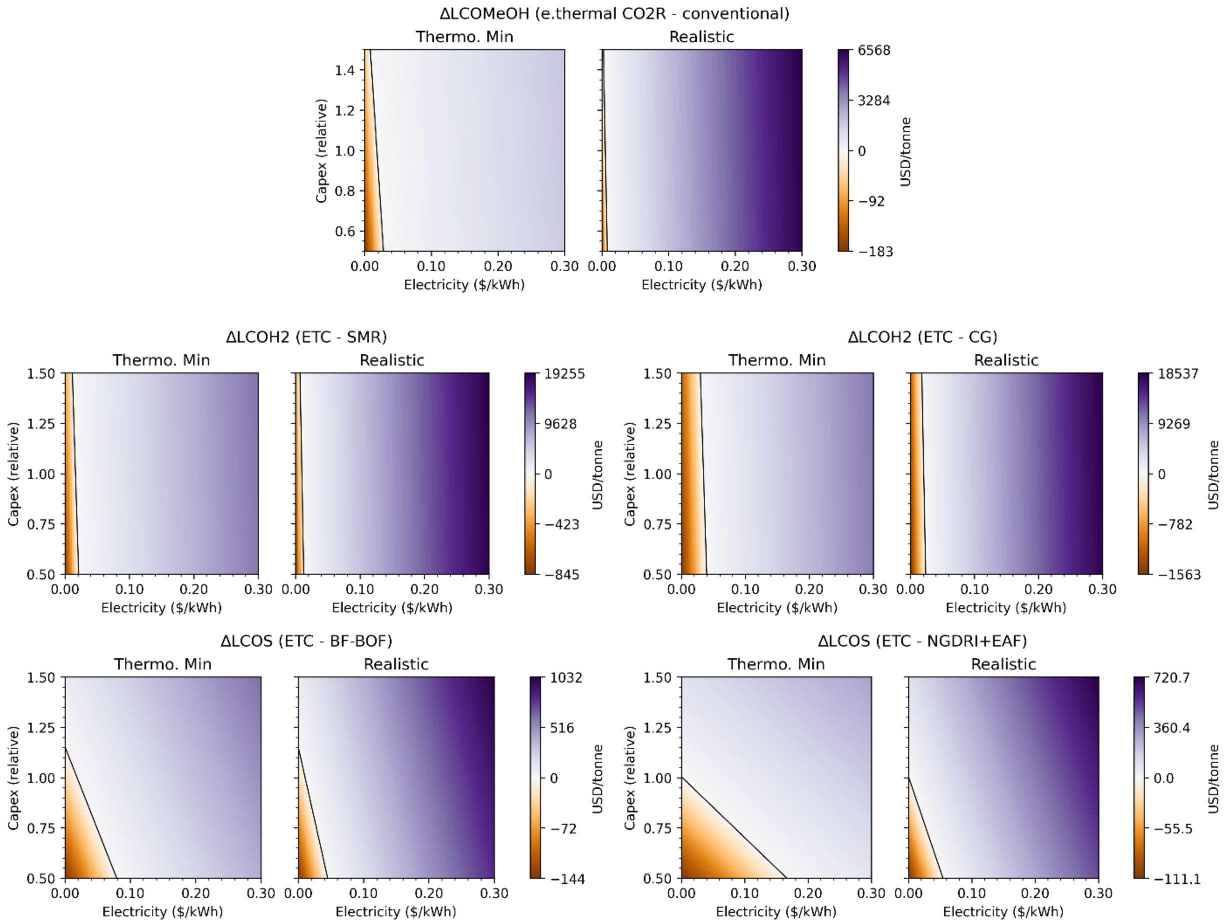


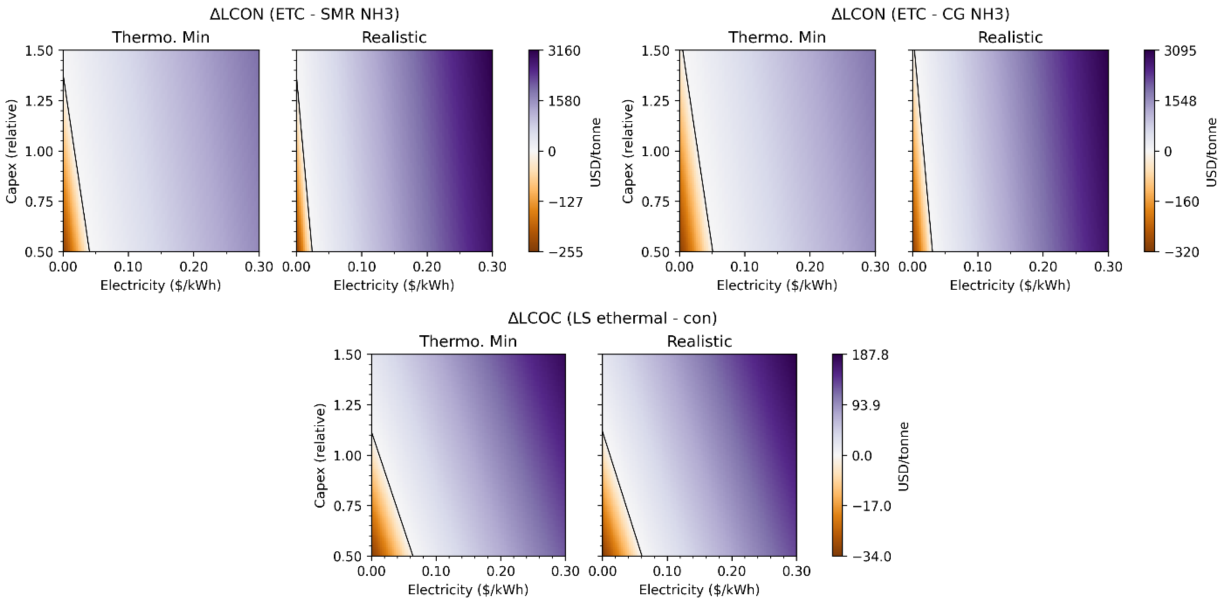


Electrothermal Decarbonization

In addition to electrochemistry, industrial processes could also be directly electrified using electrothermal approaches (the use of heat generated using electricity) by producing heat via resistive heating, plasma, or electric light.(*27*) However, for many processes of interest, direct electrothermal approaches are not feasible because the reactions of interest require temperatures that would melt any reasonable material of construction (see Supplemental Information). For these processes, we assume the same feedstocks as the decarbonized electrochemical versions, excepting fossil fuels.

Figure 4: Difference in Levelized Cost of Commodity products for electrothermal processes compared to conventional processes using thermodynamic minimum (TM) or realistic (R) electricity requirements. N.B. cement production from limestone is not fully decarbonized, as there are still process emissions associated with the decomposition of limestone. ETC = electrified thermochemical.



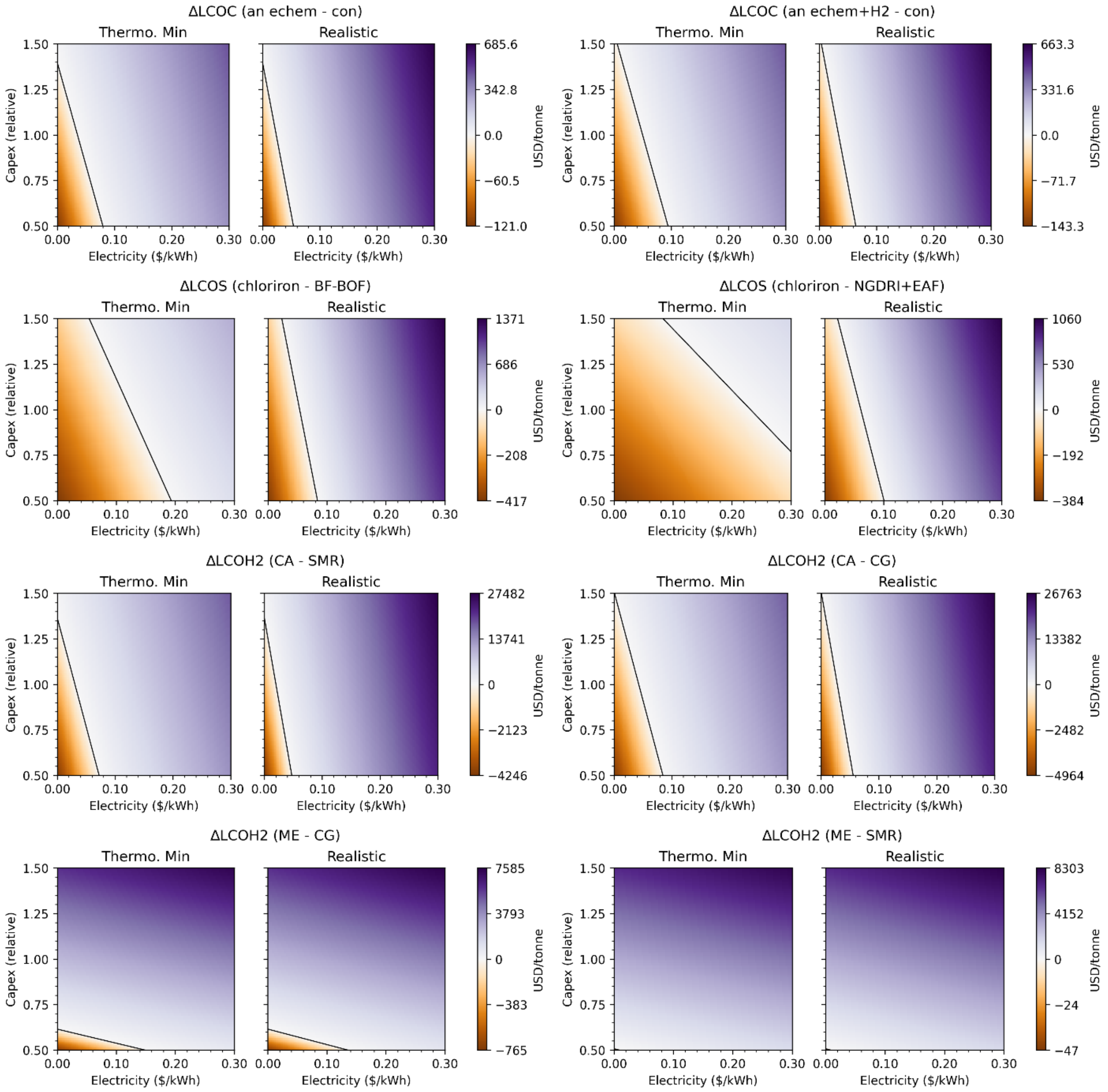


Co-Production and Decarbonization

We next analyzed novel electrified co-production schemes (where multiple products are produced in a single manufacturing plant as opposed to only a single product being produced), as in the chlor-alkali process (Figure 5, Figure 6). Our analysis indicates that multi-product electrification is cost advantaged and could lead to economical electrification, even for commodities which were barely economical or uneconomical without coproduction.

Figure 5: Differences in Levelized Cost of Cement (ΔLCOC), Steel (ΔLCOS), and Hydrogen (ΔLCOH2) for electrochemical co-production processes compared to conventional

processes. an = anorthite; CA = chlor-alkali; ME = methane electrolysis; SE = sulfur electrolysis.



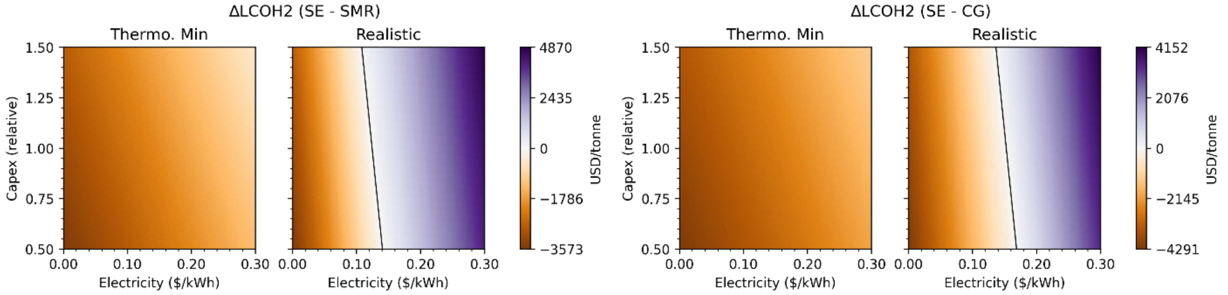
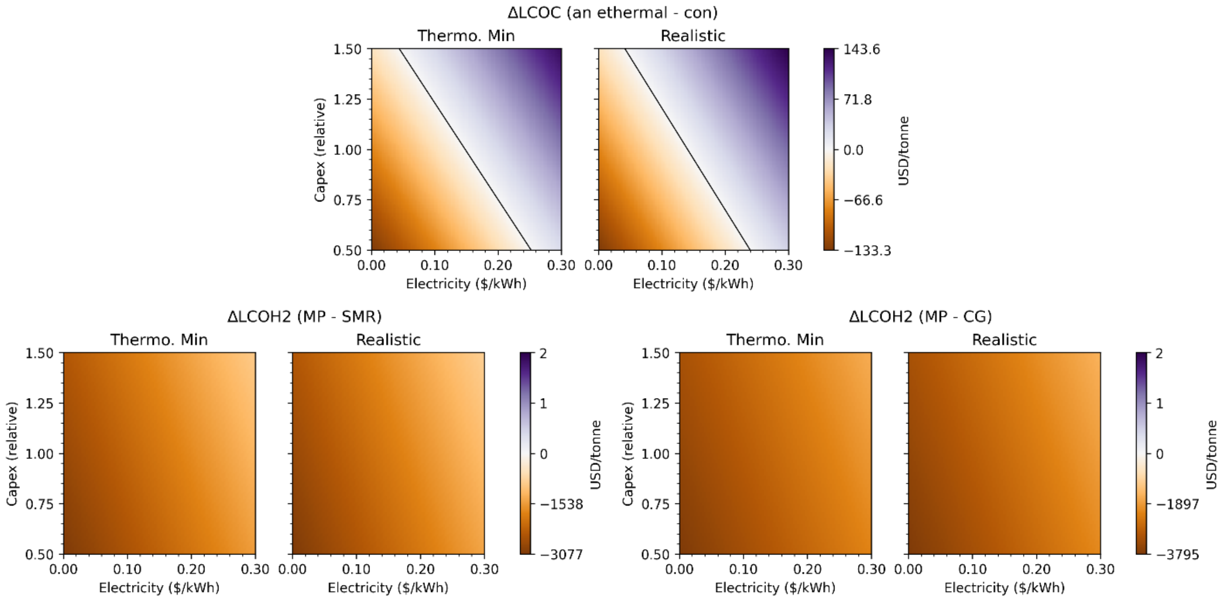


Figure 6: Differences in Levelized Cost of Cement (ΔLCOC) and Hydrogen (ΔLCOH2) for electrothermal processes compared to conventional processes.



Comparison of Electrothermal and Electrochemical Approaches

In general, thermochemical approaches (both fossil-fueled and electrified) are less expensive than their electrochemical counterparts.(*6*) However, some single-product processes still utilize electrochemistry. To understand why, we analyzed chemical oxidation or reduction reactions utilized in industry in terms of their product value per unit energy input (Figure 7).(*28*)

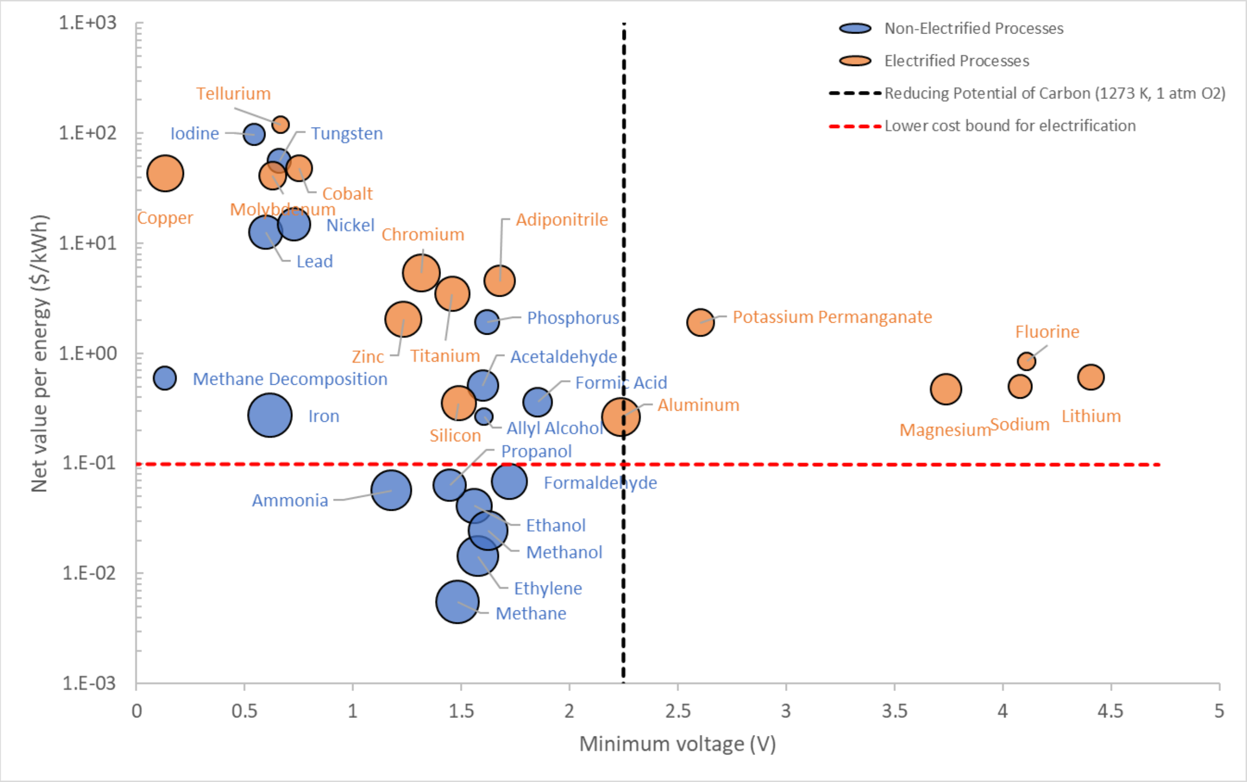


Figure 7. Commodity chemicals produced by oxidation/reduction. Orange points involve pure thermal unit operations, and blue points indicate processes that are conducted electrochemically to any appreciable extent in industry. The horizontal red line represents the empirical lower bound of feasibility for electrification in terms of dollars of product per kWh of energy used while the vertical black line represents the practical maximum reduction potential of carbon at 1000 °C. Marker sizes indicate the market volume of each commodity in tons/yr.

We use the previously published empirically determined "lower bound of feasibility" of \$0.10/kWh of product value required to justify the use of electricity.(*28*) We then add a vertical line representing the reduction potential of carbon at 1000 °C. Any process which falls to the right of this line cannot practically be performed by carbothermal reduction with fossil fuels as the heat source. The use of electricity to do work (applying a voltage, changing pressure, or changing temperature), thus, is the most direct process despite single-process chemistry.

The quadrant on the top left indicates reactions that are partially or sometimes, but not always, electrified. Here, electrification appears to primarily be driven by parsimony (e.g. fewer process steps to reach the desired product specification, lower CapEx, or co-production). This is the case for zinc production, where electrowinning of zinc offers a higher purity product in fewer purification steps, which is desirable in many applications, thereby avoiding a multi-step zinc distillation,(*29*) and has been speculated to be the case for silicon production.(*30*) This is consistent with the idea that ordered energy like electricity is better a creating ordered well segregated systems or high-purity materials, than forms of energy with lower exergy like heat. Parsimony could, thus, prove a useful decarbonization strategy for products, where high purity products are desired. However, some products require <<99% purity and therefore thermochemical processes already yield products of sufficient purity (e.g. iron and cement). Notably, cement production was excluded from this graph because it is not an oxidation or reduction, but it could be done electrochemically like any chemistry. Cement's value per kWh is <$0.01/kWh and therefore would be fall well below the lower bound of the feasibility line.

Economics of Electrification

From our modeled electrification prices, we estimated the extent of decarbonization when conventional processes are replaced with electrified processes as a function of electricity prices. We evaluate a theoretical 24-hour, zero-carbon power grid as the most optimistic scenario. Figure 8 shows that global decarbonization can economically occur at different price points of 24-hour clean electricity.

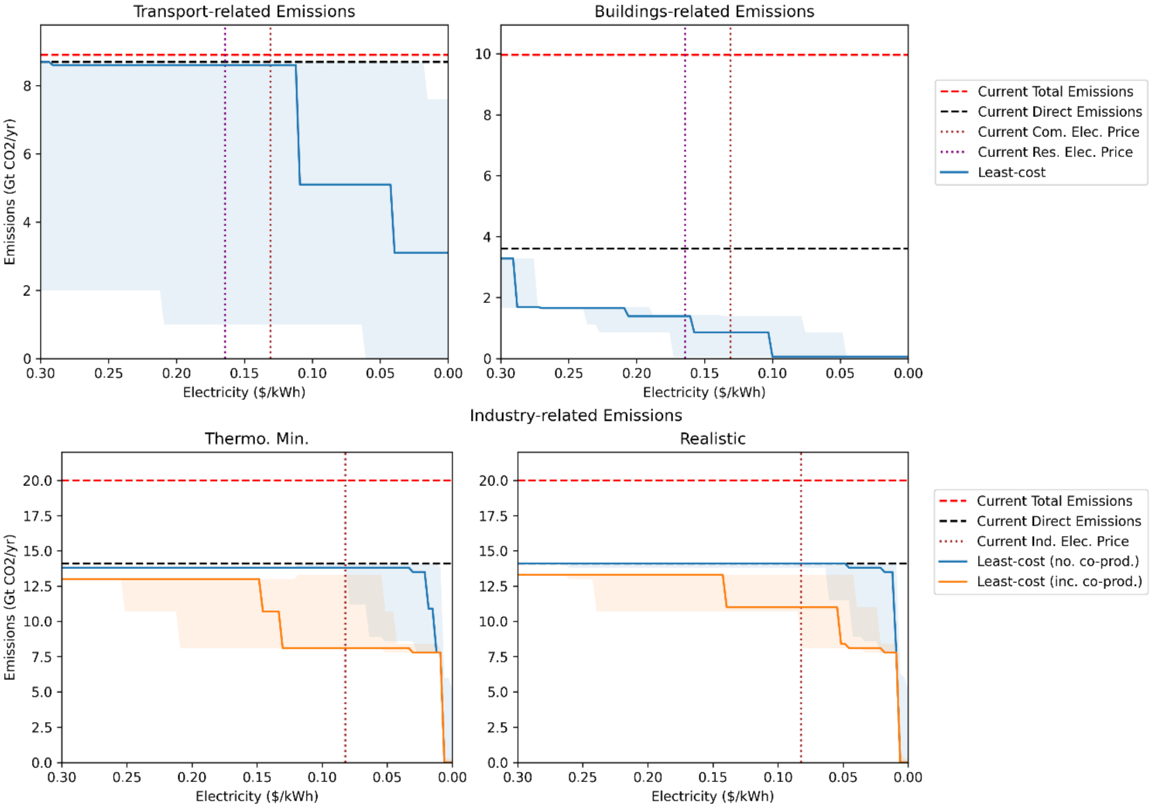


Figure 8. Transportation-, Building-, and Industry-related Emissions as a function of Electricity Price. The horizontal dashed lines indicate the emissions before and after the transition to 100% clean electricity, without any process changes. Solid blue and orange lines show further emission reduction potential resulting from transition to electrified processes. Shaded bands show emissions for ±50% calculated Electrified CapEx.

Our analysis suggests full electrification of transportation and buildings is possible with decreases in electrified CapEx and OpEx, although full electrification of transportation would require a ~50% reduction in electrified CapEx due to transportation modes with low utilization (see Figure 2). In both cases, electrification is driven by the high OpEx arising from distributed energy use and the low thermal efficiency of non-electrified transportation and buildings compared to their electrified counterparts (Figure 9).

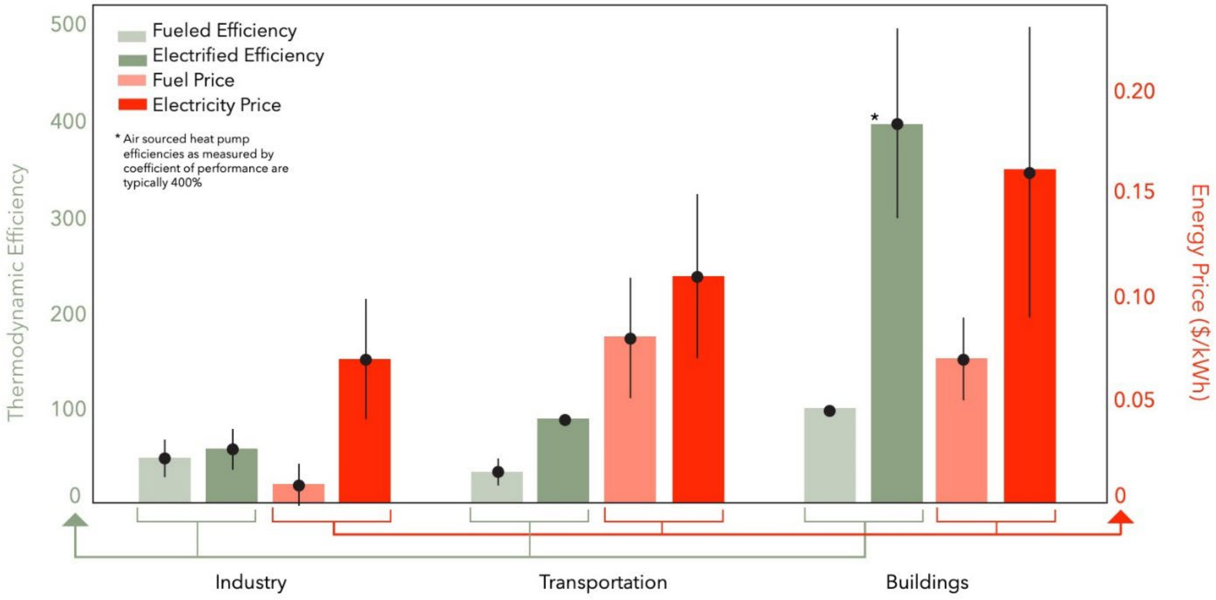


Figure 9: Efficiency versus energy price by sector. This figure shows average thermodynamic efficiency of existing state of the art fueled versus electrified systems for industry, transportation, and buildings. In industry, only electrochemistry was incorporated into the average electrified efficiency; in transportation only battery electric vehicles were considered for the electrification average, and in buildings, only heat pumps were considered as the electrified solution. Energy price data may be found in Supplemental Table 2 and efficiency data may be found in the attached spreadsheet; error bars come from averages of EIA data. Note that building sector electrified efficiency is stated as the efficiency of an air sourced heat pump as measured by coefficient of performance, typically 400%.

For industry, efficiency gains due to single-product electrochemistry, if any, are typically small, and the difference in both CapEx and OpEx suggest electrification is cost additive without significant reductions in both. Single product electrothermal processes could be cost advantaged in some cases with a 50% reduction in CapEx and large reductions in OpEx. Multi-product electrochemical and electrothermal approaches, however, could be cost advantaged with current CapEx and electricity prices.

We also evaluated whether intermittent energy could provide for cost reductions, but, as using only intermittent energy increases the relative contribution of CapEx (by decreasing the amount of product produced; refer to *Equation 1*), which is already substantial for industrial processes, this difference is insurmountable even if OpEx were free (Supplemental Figures 3-6).

Finally, we estimated the total cost of various approaches to economy-wide decarbonization to determine if a tax or subsidy could solve any additional cost of eliminating GHGs using the dominant approaches.

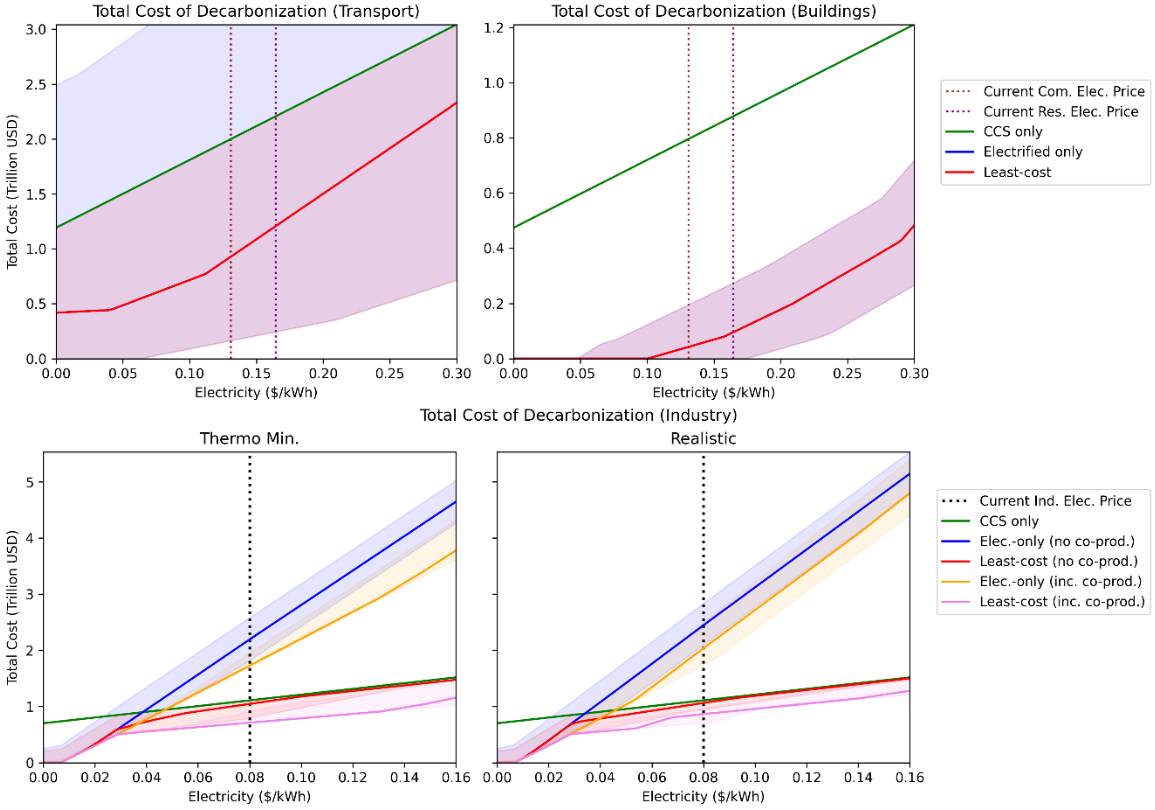


Figure 10: Cost of total decarbonization via various electrification routes, including CCS, single-product-only chemistry (SP) and co-production (CP). This figure shows the global economy-wide annual increased cost of eliminating GHG emissions versus the delivered cost of emissions-free electricity.

For industry, in some cases, point source carbon capture and sequestration (CCS) is less energy intensive than electrified production of a good or service, making the CCS-only slope shallower than pure electrification. Co-production has the capacity to decarbonize the entirety of industry at up to ~US$1T less than single product chemistry. Overall, at current electricity prices, the combination of co-production and a Capex reduction of 50% can enable electrification at <US$1T per year, or <~1% of today's global economic output.

Conclusions

Transportation

Electric trains are cost parity or better with conventional fueled trains with current electricity prices and CapEx. For cars, trucks, jets, buses, and ships, at current commercial electricity prices ($0.13/kWhr), CapEx reductions of 10%, 20%, 25%, 40%, and >50% would be required to reach parity with conventional fueled versions while at current CapEx, reductions in electricity price to $0.12/kWh, $0.05/kWh, $0.04/kWh is needed for car, ships, and jets respectively, but no electricity price reduction alone can make trucks and buses cost parity with conventional versions. Neither producing water electrolysis hydrogen nor producing carbon fuels electrochemically from CO_2 was cost parity with conventional production even with $0.01/kWh dispatchable electricity and 50% CapEx reduction. Intermittent electricity at $0.001/kWh made the economics worse. Thus, all of transportation could be economically electrified within our assumptions.

Buildings

For buildings, warm climate heat pumps represent a negligible cost above air conditioners which are often already utilized and therefore are economic with today's electricity and CapEx. In colder climates, where heat pumps have lower coefficients of performance, and where buildings often lack air conditioning, electricity prices would need to fall to ~$0.10/kWh or heat pumps would need to have a decrease in Capex of 50%, an increases in efficiency, or a combination. The other use of fossil fuels in buildings is cooking where induction stoves are competitive with gas stoves at current CapEx and electricity prices. Thus, all fuel use in buildings could be economically electrified within our assumptions.

Industry

Due to the strong dependence of levelized cost of a given commodity on Capex, electrification via intermittent energy use is uneconomical at our lowest tested electricity price ($0.001/kWh) even with a 50% reduction in CapEx. Our analysis indicates that only aluminum could be decarbonized at current industrial electricity prices ($0.08) and estimated Capex; however, aluminum is already produced electrochemically. If either CapEx or electricity became free, while the other was held at today's prices, electrochemical production and decarbonization of methanol (from CO_2), hydrogen, steel, cement, and ammonia made via single-product electrochemistry is higher cost than conventional production. A Capex reduction of 50% and 24hr electricity prices reaching $0.01/kWh or a different combination of reductions of equal or greater magnitude would be required for these chemistries to be economically competitive with conventional production. However, electrification and decarbonization at current CapEx and electricity prices can be economical with emerging co-production strategies, which produce multiple products. For all other non-electrified industrial processes, heating is the dominant source of emissions which can be done economically with current CapEx if electricity prices reach parity with fossil fuels (~$0.01/kWh), or a combination of the CapEx reductions and parity with fossil fuels (e.g. ~$0.02/kWh and electrified Capex being ~50% of conventional fossil-fueled Capex). Thus it is possible to economically electrified within our assumptions, and co-production make the cost reductions relative to today negligible while single product production requires extreme cost reductions.

With today's technologies utilizing the lowest cost energy, the additional costs for full electrification may be within a range of estimates for global willingness to pay for decarbonization. But who pays, and how these payments are sequenced – e.g. carbon pricing versus low-carbon subsidies – is key.(*31*, *32*)

Methods

Maximum GHG impact of electrification

GHGs from fossil fuels from three categories: 1) oxidation of carbon-based fuels to make CO_2 including reagent fossil fuels, 2) leakage of GHGs from mining fuel and 3) oxidation of nitrogen in the air during combustions processes. We define three broad approaches to electrification, along with the resulting GHG reductions (Table S1).

The first is electrothermal or high temperature electrification, where we simply replace fossil fuel combustion as a heat source with heat from electricity, assuming that this electricity comes from a carbon-free source. Some readers may assume that electricity cannot be used to electrify high temperature processes, but this is a misunderstanding. In fact, electricity is used for the highest temperature processes (graphite furnaces, electric arc furnaces, etc.) because it is not limited by an adiabatic flame temperature. We therefore assume that electrothermal processes will be engineerable for all thermal reactions. As shown in Table S1, this approach can eliminate the emissions from fuel consumption, but it does not impact GHGs produced from chemical reactions, greenhouse fuel gas leaks, or N_2O production. In the second electrification scenario, electrothermal processes are further replaced with either air-free thermal processes (which would avoid N_2O production because there would be no high temperature N_2-O_2 mixture to oxidize N_2) or low temperature electrochemical or catalyzed thermal processes that use the same petrochemical feedstocks. This eliminates the small fraction of GHG emissions from unwanted nitrogen oxidation. In the third scenario, we further replace petrochemical feedstocks with non-GHG alternatives, eliminating all fossil fuel-related emissions.

In principle, these approaches could be mixed and matched and high temperature processes could be used in air but without using greenhouse fuel gases thus eliminating leaks but not eliminating N_2O. In the analysis below we assume that both electrothermal and electrochemical routes could eliminate N_2O.

Modeling Electrification

We delineate GHG emissions in separate categories which individually contribute to overall emissions. The main categories are electricity generation, transportation, direct use of fuel in buildings, industrial use, and non-fossil emissions. We made the assumption that electricity generation was emissions-free to allow for maximal emissions reductions from electrification.

For all models, the levelized cost is derived from the following:

$$LCOX = \frac{\sum_{t=0}^{t=lifetime} \frac{CapEx(t) + OpEx(t)}{(1+r)^t}}{\sum_{t=0}^{t=lifetime} \frac{X\ (distance, product\ produced)}{(1+r)^t}}$$

Equation 1. Levelized cost of X (LCOX).

For all models, a discount rate of 15% was used.

Transportation

Within this sector, the leading approach to electrification involves replacing combustion engines with electric motors, while retaining vehicle form factor. This approach benefits from the high efficiency of electric motors (typically 90%) and the relatively low efficiency of small combustion engines (typically 25-45%).(*8*) Transportation electrification also benefits from the fact that fuels sold at small scales for filling fuel tanks on a distributed network are substantially more expensive per unit energy than large scale centralized fuel consumption like in a chemical plant (Tables S2 and supplemental data). The efficiency differential makes up for the relatively high cost of electricity as compared to liquid fossil fuels. Other electrified approaches involve making "e-fuels" which are analyzed separately compared to conventional fuel production technologies in the industrial section below.

We started our analysis of transportation by using industry standard thermodynamic efficiencies of fueled engines (supplemental data spreadsheet) within each transportation category and comparing them to the thermodynamic efficiency of a modern electric motor (~90% regardless of size).

We estimated the electricity price required for energy consumption of an electrified system to reach cost parity with the energy price of a fossil-fueled system for lowest assumed price of fuel (full market adoption) for different vehicle products (supplemental data spreadsheet), using a levelized cost of distance metric that assumes use immediately after purchase (at t=0), and constant annual miles traveled:

$$LCOD = \frac{CapEx + \sum_{t=0}^{t=lifetime} \frac{OpEx}{(1+r)^t}}{\sum_{t=0}^{t=lifetime} \frac{annual\ miles\ traveled}{(1+r)^t}}$$

Equation 2. Levelized cost of distance (LCOD, US$/mi).

We then estimated the lifetime cost of ownership (CapEx + OpEx) of electric versus fueled transportation. For buses (1.0% of GHG emissions), trains (0.6% of GHG emissions), cars (6.9% of GHG emissions), and trucks (5.1% of GHG emissions), using the real CapEx of both fossil powered and electric vehicles. For ships (1.9% of GHG emissions) and planes (1.9% of GHG emissions), we assumed that the electrified CapEx was the average ratio of the CapEx of known electrified transportation categories to fossil fueled categories multiplied by the fossil-fueled CapEx.(*33*) For the OpEx fuel price, we assumed present day fuel prices and we varied electricity prices from \$0.00/kWh to \$0.30/kWh and multiplied this by the annual average distance traveled by the transportation type and the energy economy (GJ per mile). Details on CapEx and OpEx calculations as well as references may be found in the supplementary data spreadsheet. Again, we used real average fuel/electricity economies when known and estimated the electricity economy for ships and planes in the same manner as CapEx above (supplementary data spreadsheet). In all cases, we ignored maintenance costs because while some sources indicate that electric vehicles will require less maintenance, the CapEx of the vehicle is more expensive which indicates that the replacement parts would be more expensive and therefore it is not clear if lifetime maintenance is actually lower cost. Further research is needed to understand independent lifetime cost of maintenance studies. We ignore practical limitations such as the energy density of batteries which would likely need to be solved to electrify air travel while maintaining modern cargo, passenger loads and thus revenue.(*34*)

We also performed a LCOD analysis using e-fuels from CO_2, with identical efficiencies and CapEx as conventional fueled vehicles. The price of e-fuels was determined using an OpEx-only analysis, and showed that the high energy associated with making e-fuels from CO2 is unlikely to drive electrification (see Supplemental Information).

For emissions calculations, we assumed each transportation mode had equal electrification-associated contributions to GHG emissions.

Buildings

Fuel use in buildings is primarily for space and water heating (96%), with minimal contribution from cooking (4%). Resistive electric heating and heat pumps were considered as substitutes for electrification of space and water heating. We compare the lifetime cost of heat pumps, resistive electric heating, and natural gas heating for AHRI Region III (Southern US), Region IV (mid-Atlantic and midwestern US), and Region V (e.g. northern US, Canada), with different heating loads and associated efficiencies, and make the simplifying assumption that space heating and water heating would have similar LCOH.

$$LCOH = \frac{CapEx + \sum_{t=0}^{t=lifetime} \frac{OpEx}{(1+r)^t}}{\sum_{t=0}^{t=lifetime} \frac{Annual\ heating\ load}{(1+r)^t}}$$

Equation 3. Levelized cost of heating (LCOH, USD/GJ).

To be generous to the electrified cases, we assumed new build construction instead of retrofit addition such that CapEx factors into both decisions, with a 15 year lifetime for all heating sources. When air conditioning is installed, we considered a marginal heat pump cost of $0 in Region III, $1000 in Region IV, and $2000 in Region V to account for the increased system sizes required to match the heating load.

For heat pumps, we assumed that the Heating Seasonal Performance Factor (HSPF2) for Regions III, IV, and V, were 9.0, 7.5, and 6.0, respectively, consistent with relevant literature values.[44] Detailed assumptions including references for CapEx and OpEx of various heating types may be found in the supplementary data spreadsheet. The annual heat supplied is set at 37.5 GJ, 50 GJ, 75 GJ for Regions III- V, respectively, and the OpEx is the average heating demand divided by the efficiency, which we set as 0.95 for natural gas furnaces, 1.0 for electric resistive heating, and the corresponding seasonal average Coefficient of Performance (HSPF2/3.41) for heat pumps.

For emissions calculations, we assume that 90%, 75%, and 25% of households in Regions III, IV, and V, respectively, will always opt for air conditioning, in which case the installed heat pump cost will be equal to the marginal cost difference between heat pumps and AC.

Industry

In this analysis, we considered a subset of major and minor industrial processes that use carbon as a reagent. The five industrial products produced by these processes represent ~40% of industrial GHG emissions. We started by analyzing mainstream technologies which we define as single product processes which are direct substitutions for the conventional single-product method. We did this analysis first by assessing energy consumption alone and then including CapEx and other OpEx to do a comparative levelized cost analysis.

We calculated levelized costs of industrial processes assuming a one-year build time, a 25-year lifetime, and a 90% capacity factor according to the following equations:

$$LCOX = \frac{CapEx + \sum_{t=1}^{t=lifetime} \frac{OpEx}{(1+r)^t}}{\sum_{t=1}^{t=lifetime} \frac{Product}{(1+r)^t}}$$

Equation 4. Levelized cost of any given product (LCOX), assuming a one-year build time.

Our OpEx includes feedstock price, as many novel electrochemical processes tout cheaper feedstocks as a key advantage (supplemental data spreadsheet). We consulted retail values to obtain the LCOX of the conventional route which were expected to be (and were in fact) always higher (+/-50%, Table S8).

If the chemical reaction in question produces CO_2 from reagent hydrocarbons, then we would consider other chemical reactions which do not produce CO_2 as a byproduct. These other chemical reactions include hydrogen production from water splitting in place of steam methane reforming (SMR) and coal gasification (CG), electrochemical steel production with an inert anode, hydrogen direct reduction of iron ore, and aluminum production with an inert anode. In the case of cement, which produces CO_2 from decomposing limestone to make lime ($CaCO_3 \rightarrow CaO + CO_2$), we considered both a process which uses limestone as the calcium source as well as a process which uses silicates as a Ca source.

We then analyzed novel chemistries which co-produced multiple chemicals; the co-production processes produced hydrogen, chlorine, and caustic soda; hydrogen and carbon black; hydrogen and sulfuric acid; steel, chlorine, and caustic soda; and ordinary portland cement and supplementary cementitious materials. The exact chemical reactions analyzed may be found in the Supplemental Information and supplementary spreadsheet).

Using the above assumptions, for both the conventional production route and the theoretical electrochemical production route, we calculated the difference between levelized cost of the electrified product and the levelized cost of the conventional products under the electricity price range up to $0.30/kWh, with electrified CapEx ranging from 50% to 150% of the calculated electrified CapEx. For the conventional route, we used industry data and ensured that our calculated levelized costs of production agreed with publicly available data.

Electrochemical Decarbonization

We estimated the CapEx of a theoretical scaled electrochemical reactor for a given chemical reaction by using an empirical method.(*26*) The certainty of these CapEx estimates are +100% / -50%, but we analyzed ±50%. We assumed a lifetime of 25 years.

Each electrochemical process will have an associated current density (and efficiency that is a function of current density) that minimizes the levelized cost of the associated product. The precise current density depends on relative CapEx and OpEx contributions, with the latter strongly dependent on the cost of electricity). Initial modeling suggested that 1) CapEx was a significant portion of the levelized cost for the electricity prices surveyed, 2) higher current densities minimized the levelized cost for typical electricity prices, and 3) electrochemical processes only reached parity at low electricity prices.

Because electrochemical processes only reached cost LCOX parity at low electricity prices, where CapEx made up a greater percentage of levelized cost, we made the simplifying assumption to use the highest available current density in literature under the assumption that this would minimize the levelized cost. In the event that the highest available current density was lower than other processes of similar temperatures, we assumed the current density could reach empirical values for electrochemical processes performed at similar temperatures using the same empirical method.

We also estimated OpEx costs based on the best literature current densities or closest analogous electrochemical industrial process; we called this the “Realistic” case. We also analyzed the ideal 100% efficient “Thermodynamic Minimum” case. We then compared the levelized cost of electrochemical production to the levelized cost of thermochemical production based on energy consumption and CapEx for thermochemical plants (Supplemental Figures). The chemical reactions and energy prices that we analyzed are found in the supplementary spreadsheet.

Electrothermal Decarbonization

In general, thermochemical electrified CapEx is between cost parity and 50% higher cost than conventional fuel fired CapEx (Table S3).(*35*) However, because electrified heating can be more efficient, it is possible that electrified CapEx could be cheaper like it is for resistive space heating and may be for steam methane reforming.(*36*) In order to be optimistic for electrification, we assume that electrothermal CapEx values are those of conventional

CapEx, ±50%. For OpEx, we examine the thermodynamic minimum energy consumption starting from non-fossil feedstocks, and assume that the realistic efficiency achieved is that of the fueled process. For the realistic efficiency of fueled processes, we divide the sum of the enthalpic contribution and reagent equivalent energy contribution by the total energy consumption.

The production of steel, hydrogen from water, and aluminum production in the absence of a reducing agent is exergonic only above ~3,000 °C, ~5,500 °C, and ~10,000 °C, respectively, suggesting implementation of an electrothermal process could be challenging. Therefore, the utilization of a regenerable reducing agent (as in thermochemical cycles[47]) may be necessary for achieving 50% cost reduction without the use of exotic materials or processes.

Lower Cost, Intermittent Energy

For low cost, intermittent energy, we assume that electricity could be free (OpEx = US$=0), and calculate the levelized cost according to *Equation 1* using 50% CapEx and a 20% Capacity factor.

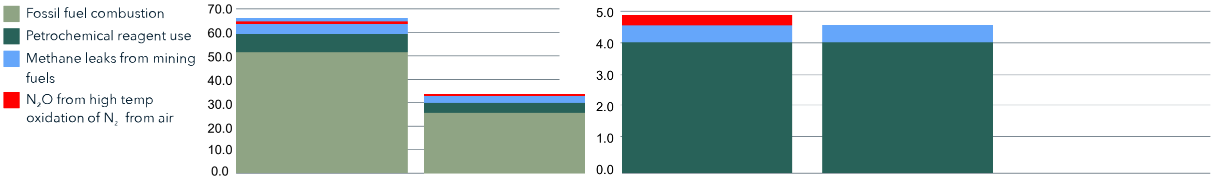
Economics of Electrification and Total Cost of Decarbonization

For the analysis in Figure 8, we first assumed that indirect emissions due to electricity and heat generation would drop to zero. We made the simplifying assumption that as soon as a technology reached cost parity, policy solutions would ensure that the electrified technology replaced the conventional technology, and direct emissions would fall. This analysis is therefore again conservative, as cost parity is typically not enough for a new, riskier technology to replace a well-understood conventional technology with fully amortized CapEx. For single-product-only chemistries, this primarily resulted in an elimination of electrochemistry and utilization of electrothermal solutions. For all sectors which were not analyzed, we assumed they would reach cost parity once electricity and heat prices reached cost parity, similar to electrified thermal solutions at an electrified CapEx of 100%.

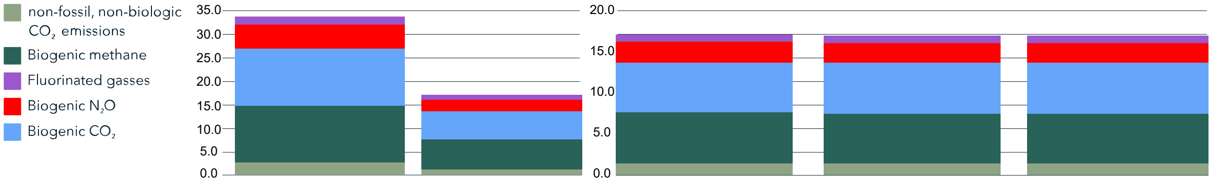
For the analysis in Figure 10, we calculated the least-cost decarbonized method of production (including electrification using single-product and co-production chemistries, as well as CCS) of every sector analyzed in this paper which using Equation 1 and data from the supplemental spreadsheet. Importantly, we only consider cost increases in this analysis, and ignore cost decreases. This is because we do not consider it to be politically feasible or incentivizing of electrification to take cost reductions from electrification of one industry (for example via an industry specific tax for being economically feasible to electrify) and reallocate them to another unrelated industry (for example via a subsidy). Industry specific and point source CCS costs were taken from the US Department of Energy's National Energy Technology Laboratory (NETL) and the International Energy Agency (IEA), whichever were lower cost, and may be found in the attached spreadsheet, and scaled CCS cost with electricity cost.(*37*, *38*) We assume the remainder of industrial GHG emissions to be eliminated by electricity reaching cost parity with fossil fuels. For the remainder of GHG emissions, we assign a CCS cost of $50-200/tonne CO2, which we justify given that these are primarily direct emissions, the concentration of CO2 in the flue gas should be higher than DAC, and, as cost scales with concentration, cost should be more similar to process-specific costs than DAC costs. For distributed sources, including transportation and buildings, we use DAC costs for CCS.

Supplemental Information

Supplemental Table 1. Contribution to total GHGs from various sources and the potential for electrification to eliminate emissions.



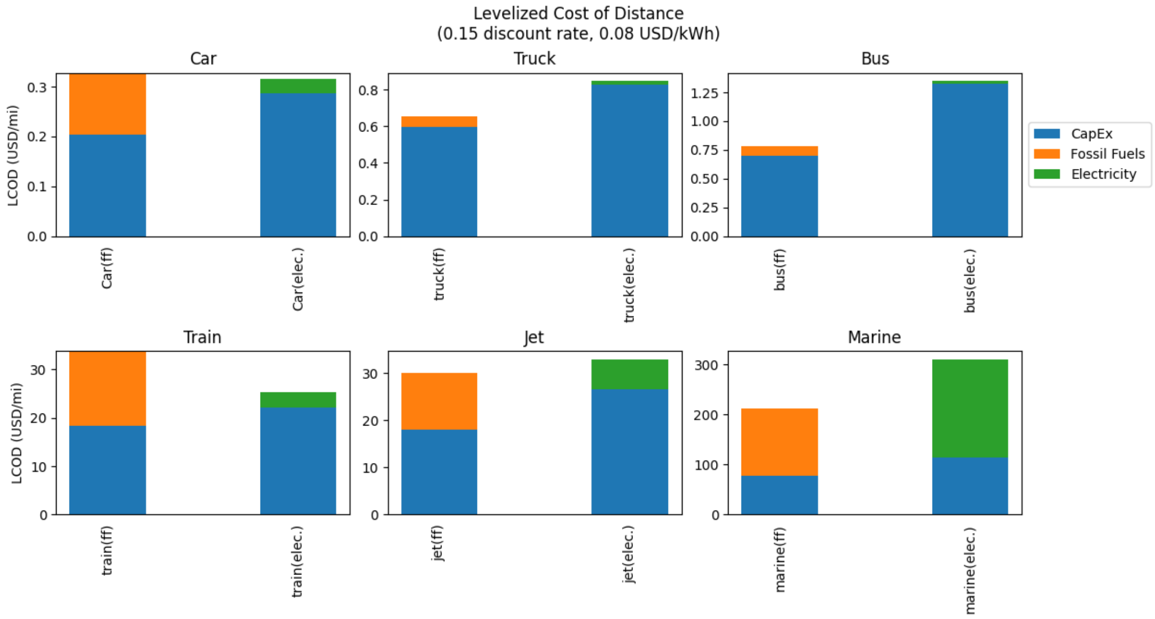
	% of GHGs	GHG in petagrams CO_2e	High temp electrification in air in petagrams CO_2e	Low temp or air-free electrification in petagrams CO_2e	Elimination of reagent fossil fuels + low temp or air free electrification in in petagrams CO_2e
Total GHG contribution from fossil fuels	66.5	36.5	4.8	4.5	0.0



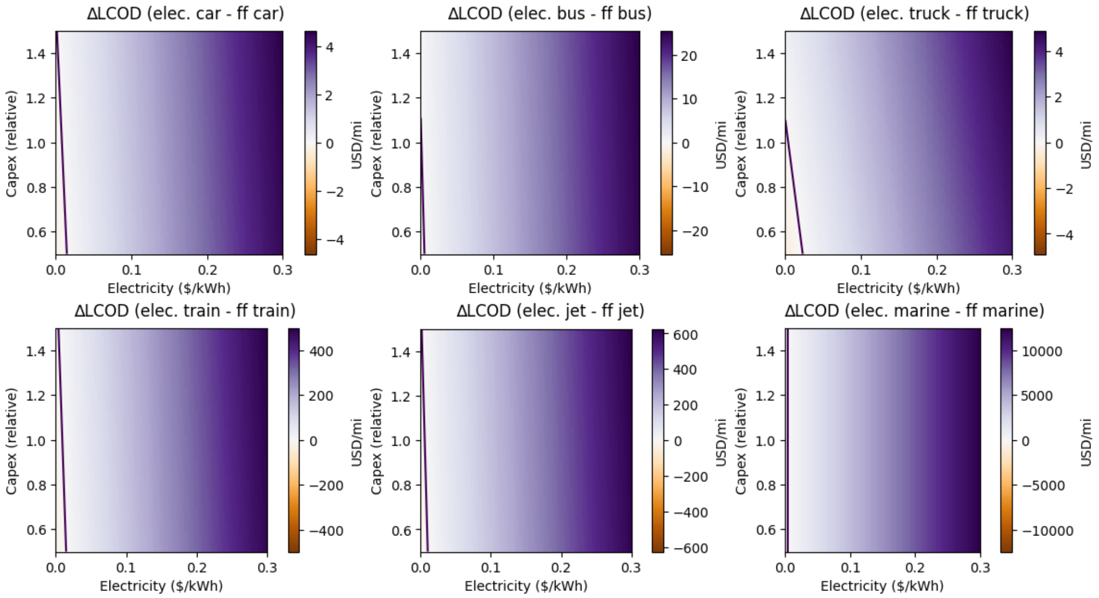
	% of GHGs	GHG in petagrams CO_2e	High temp electrification in air in petagrams CO_2e	Low temp or air-free electrification in petagrams CO_2e	Elimination of reagent fossil fuels + low temp or air free electrification in in petagrams CO_2e
Total GHG contribution from non-fossil fuels	33.5	18.5	17	16.9	16.9
Total GHG contribution	100	55	21.8	21.4	16.9
% reduction in GHGs	-	-	**57**	**58**	**67**

Transportation

Engine efficiencies, CapEx, and OpEx assumptions for transportation may be found in the attached spreadsheet.



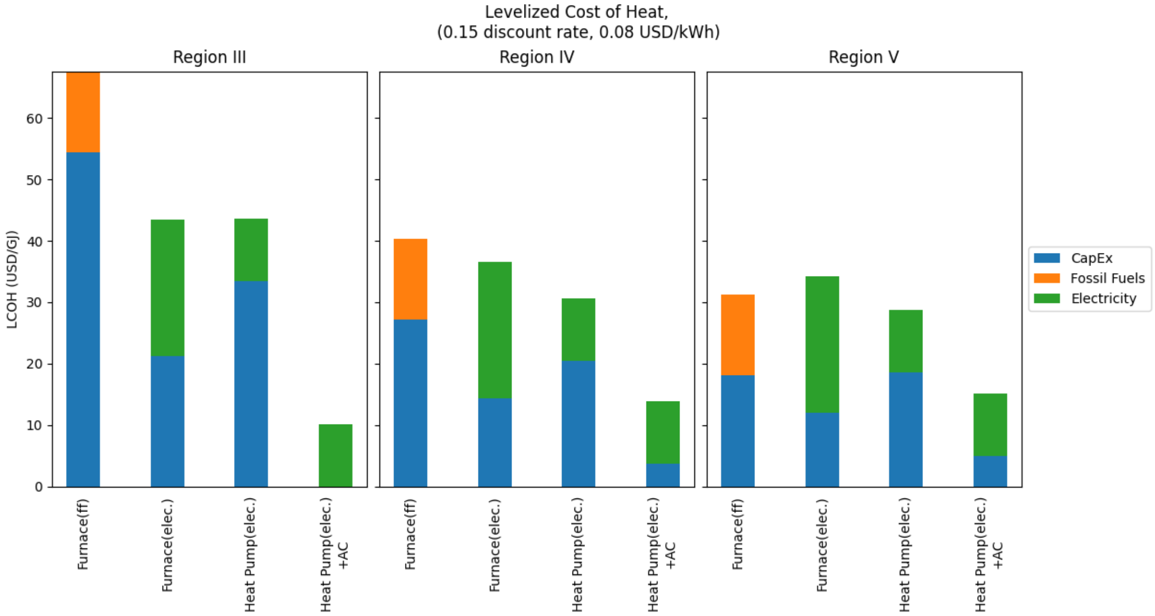
Supplemental Figure 1. Calculated Levelized Cost of Distance for selected electrified and fossil fueled modes of transmission.



Supplemental Figure 2. Calculated Levelized Cost of Distance for E-fuels, with the price of E-fuels representing an OpEx-only analysis.

Buildings

Building heating data may be found in the attached spreadsheet.



Supplemental Figure 3. Levelized cost of Heat for selected electrified and fossil fueled heating options in different Regions.

Industry

Electrochemical Decarbonization

Energy requirements for industrial reactions may be found in the attached spreadsheet.

For water electrolysis, we made the simplifying assumption that water does not require stringent front-end handling for electrolysis, and assumed no additional front-end processing, so the estimated electrochemical CapEx only considers electrolysis/product handling and rectifier costs.

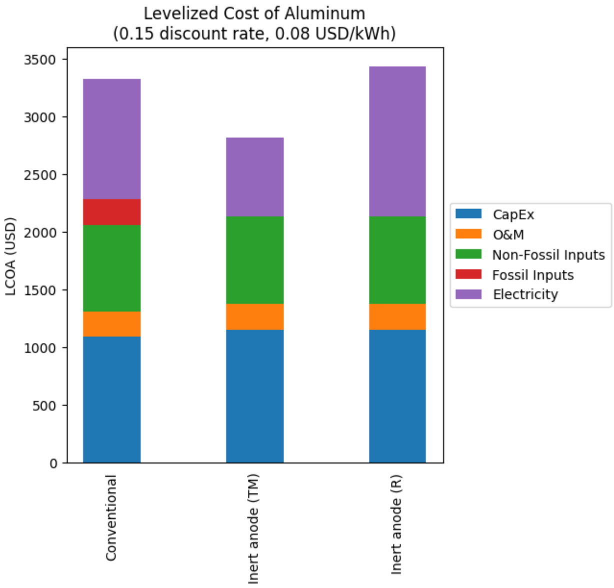
For electrochemical cement, we consider the case of leaching Ca from limestone/anorthite with HCl, precipitating $Ca(OH)_2$ with NaOH, then regenerating HCl and NaOH using the chlor-alkali process. It is worth noting that the chlor-alkali process may overestimate the energy required for leaching, as it is not strictly necessary to generate H_2 and Cl_2, but it may be possible to generate HCl and NaOH using a hydrogen-depolarized anode, bipolar membrane electrodialysis, or similar. Leaching and $Ca(OH)_2$ precipitation are exothermic, and are not considered in the energy calculations. In these hypothetical processes, portland cement is clinkered from $Ca(OH)_2$. The energy contribution for acid/base regeneration and clinkering ends up being the same for both reactions; the major difference is the existence of co-products. We also consider the possibility of using direct electrosynthesis to produce HCl, NaOH, H_2, and O_2; for this, we estimate the electrical requirements as the same as the chlor-alkali process. For CapEx, we assume that the front-end processing is already included in the CapEx required for a cement plant, so the estimated electrochemical CapEx only considers electrolysis/product handling and rectifier costs, similar to other treatments.(*39*)

For aluminum, we assume molten oxide electrolysis electrolysis at 1000 °C using an inert anode. This results in an estimated CapEx similar to the Hall-Heroult process; differences arise in the rectifier cost due to the higher operating voltage. We assume the inert anodes are truly inert and do not require replacement.

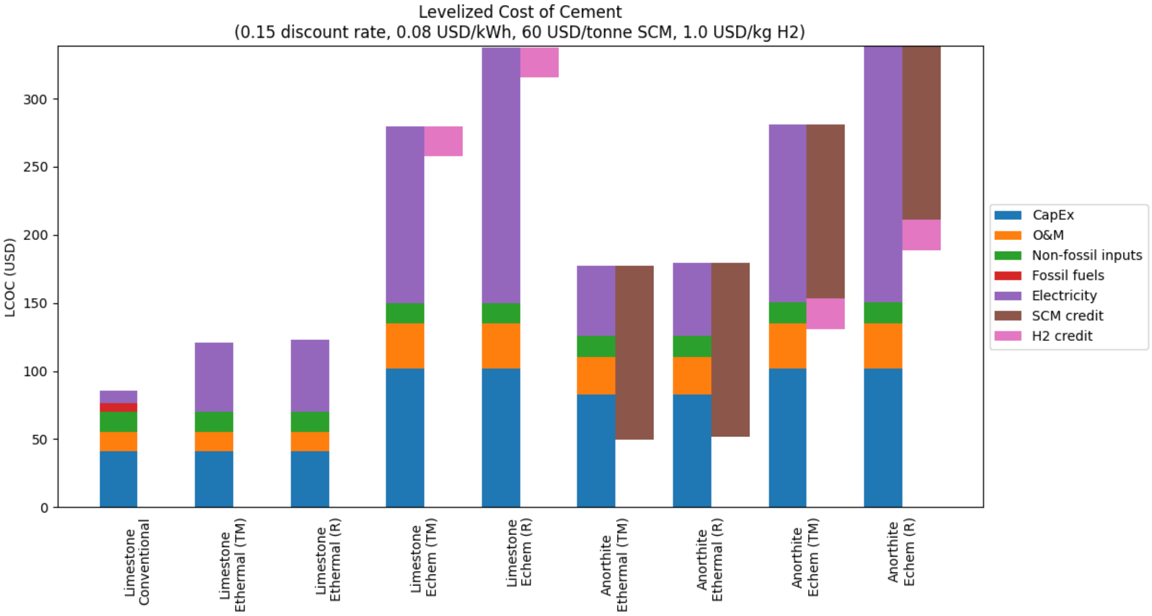
For all methods of steel production, we assumed EAF energy consumption for steelmaking was the same as conventional across all processes in which it is employed. For steel production via molten oxide electrolysis using an inert anode, we assume electrolysis at 1600 °C, with inert anodes that do not require replacement. For steel production via water splitting and H_2 DRI, we used different efficiencies for water splitting and for the heat required for directly reducing iron. We assumed EAF energy consumption for steelmaking was the same as conventional across all processes. For this process, because water is capable of recycling or does not require stringent front-end handling, we assume no additional front-end processing, so the estimated electrochemical CapEx only considers electrolysis/product handling and rectifier costs.

Electrothermal Decarbonization

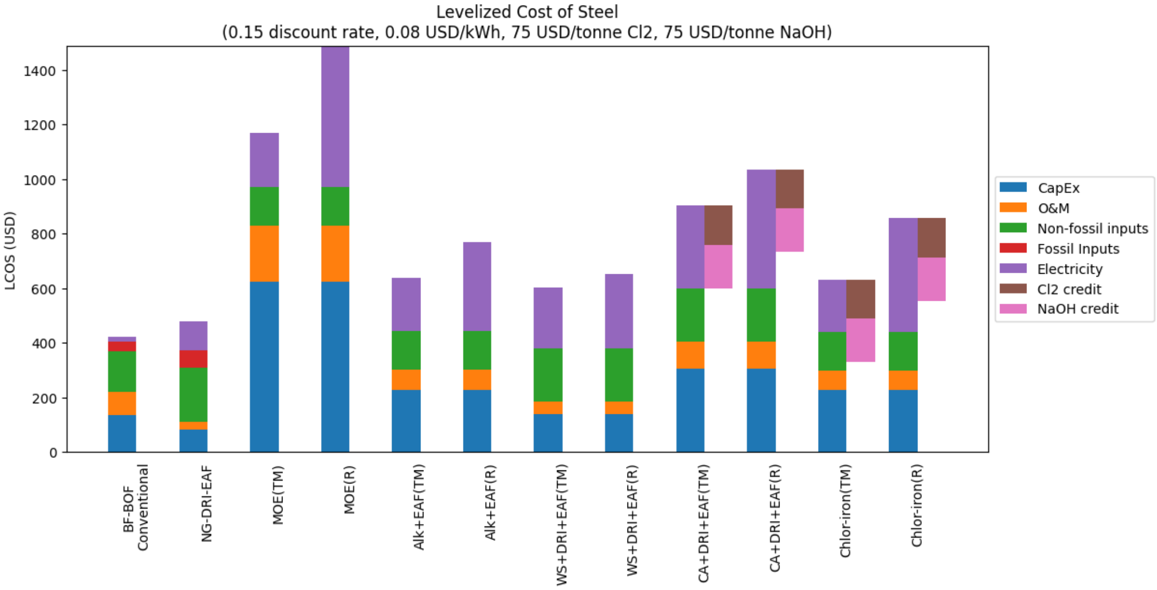
Energy requirements and CapEx for industrial reactions may be found in the attached spreadsheet.



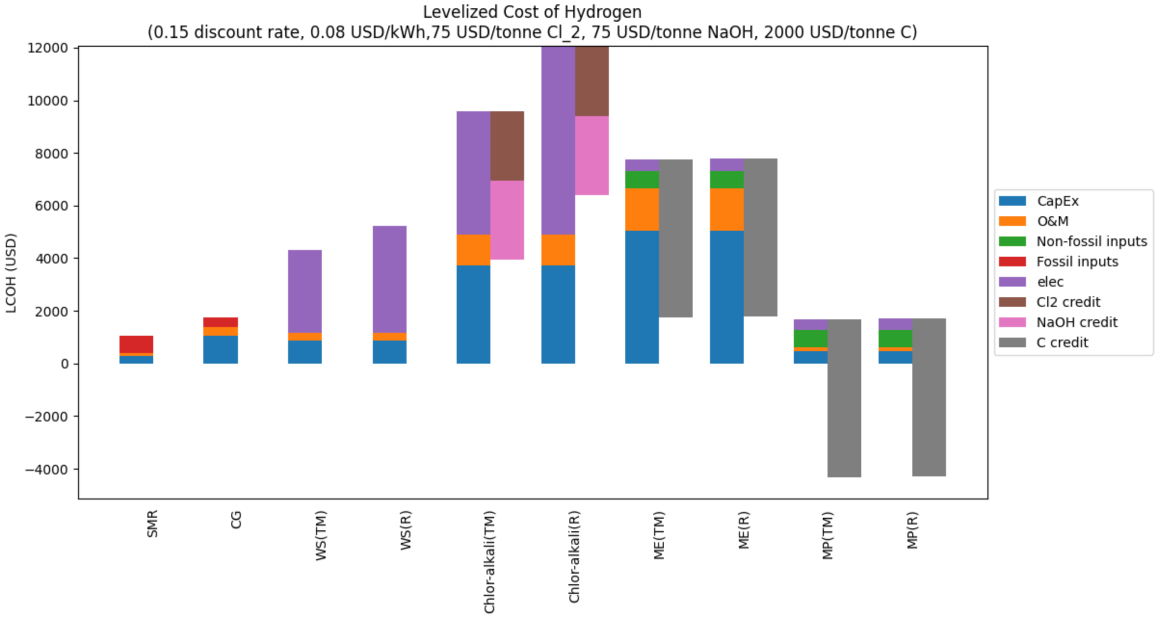
Supplemental Figure 4. Calculated Levelized Cost of Aluminum



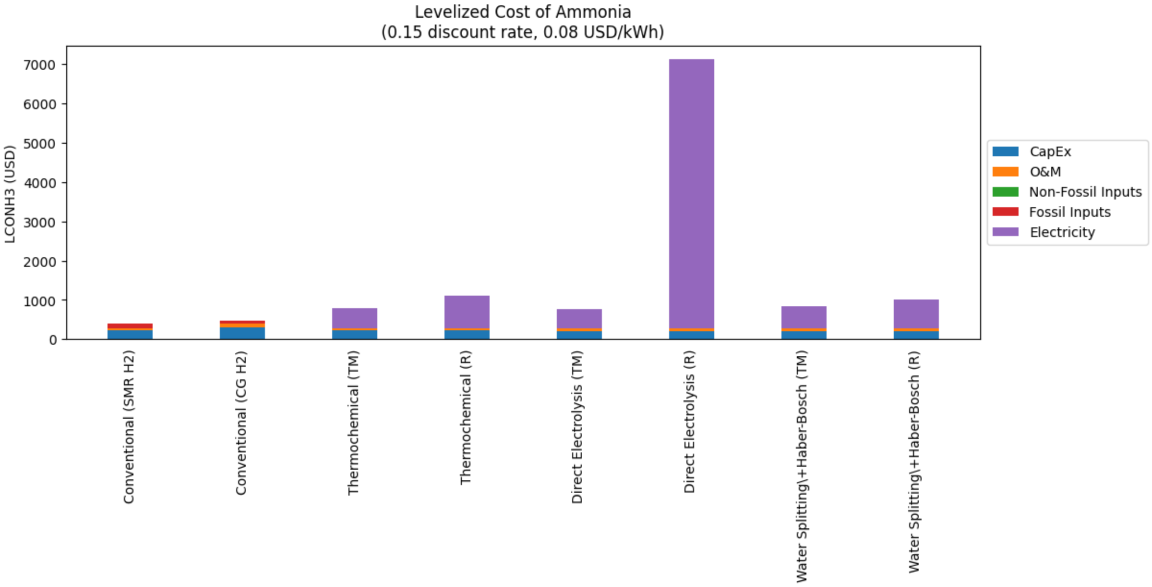
Supplemental Figure 5. Calculated Levelized Cost of Cement



Supplemental Figure 6. Calculated Levelized Cost of Steel

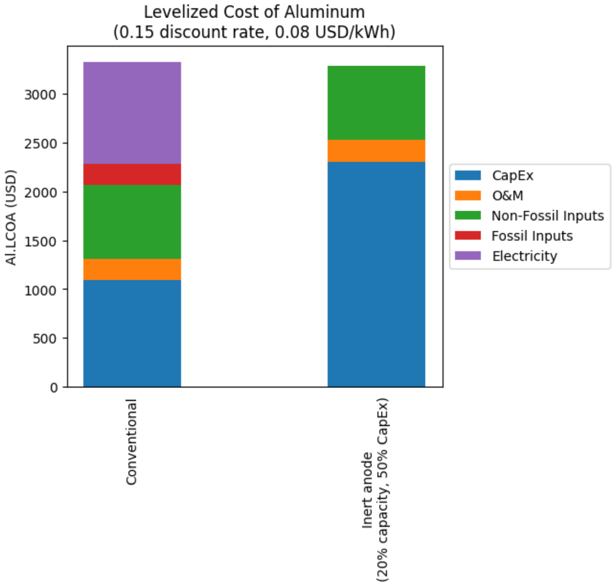


Supplemental Figure 7. Calculated Levelized Cost of Hydrogen

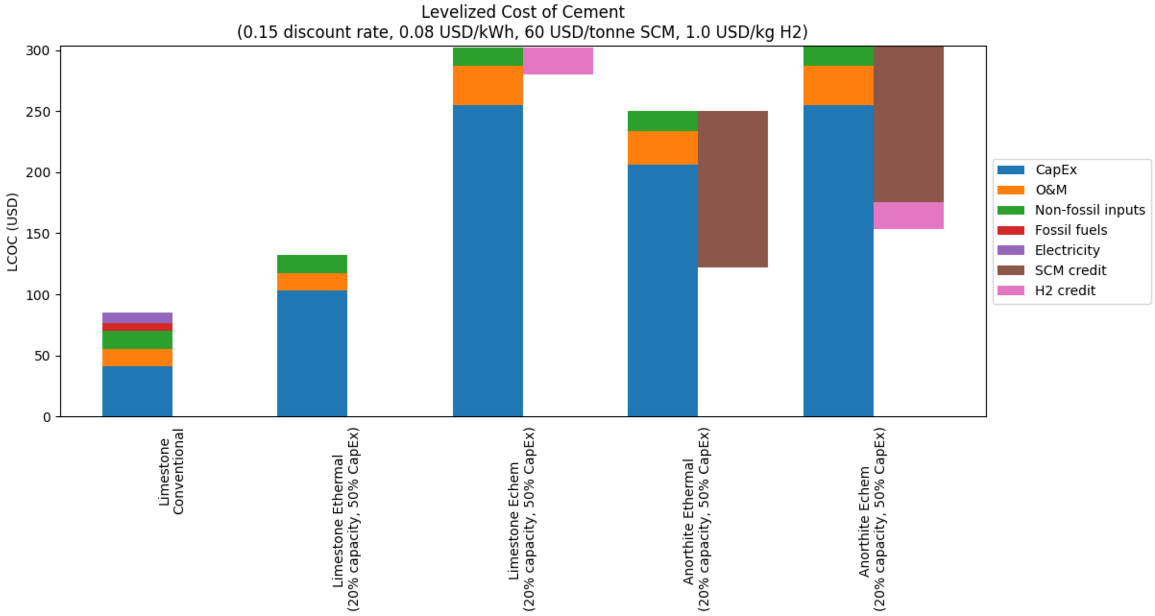


Supplemental Figure 8. Calculated Levelized Cost of Ammonia

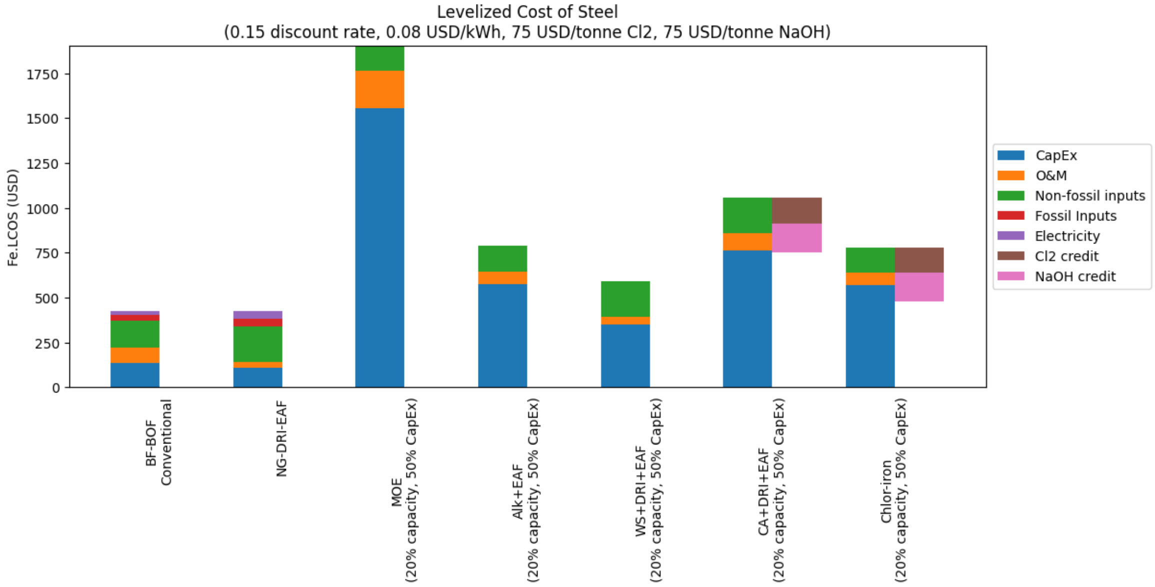
Lower Cost, Intermittent Energy



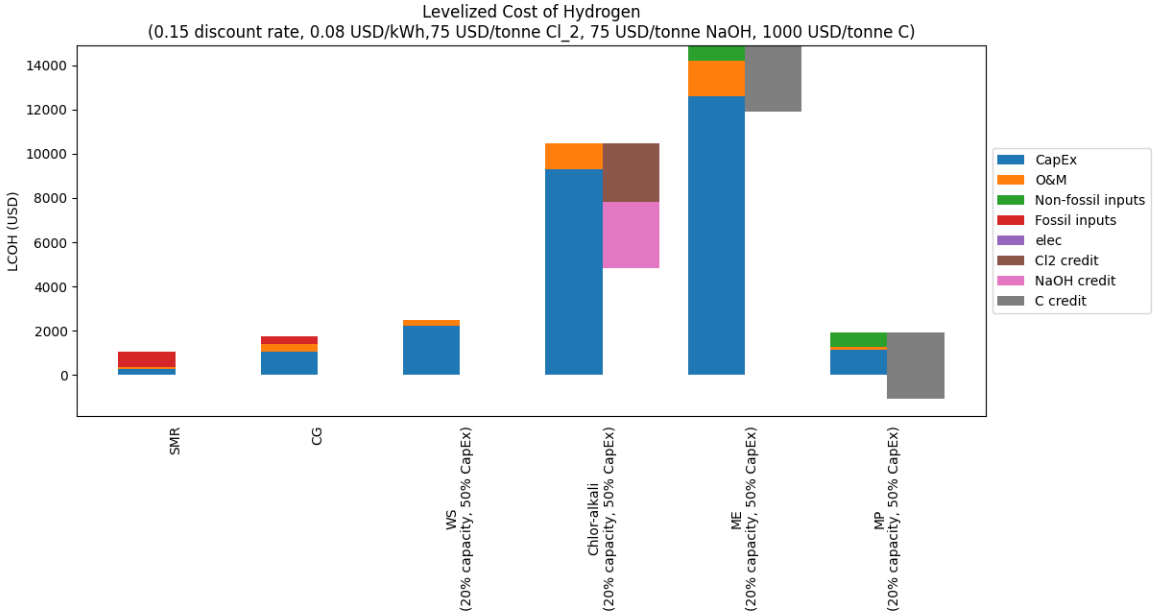
Supplemental Figure 9. Calculated Levelized Cost of Aluminum (50% CapEx, 20% Utilization Factor)



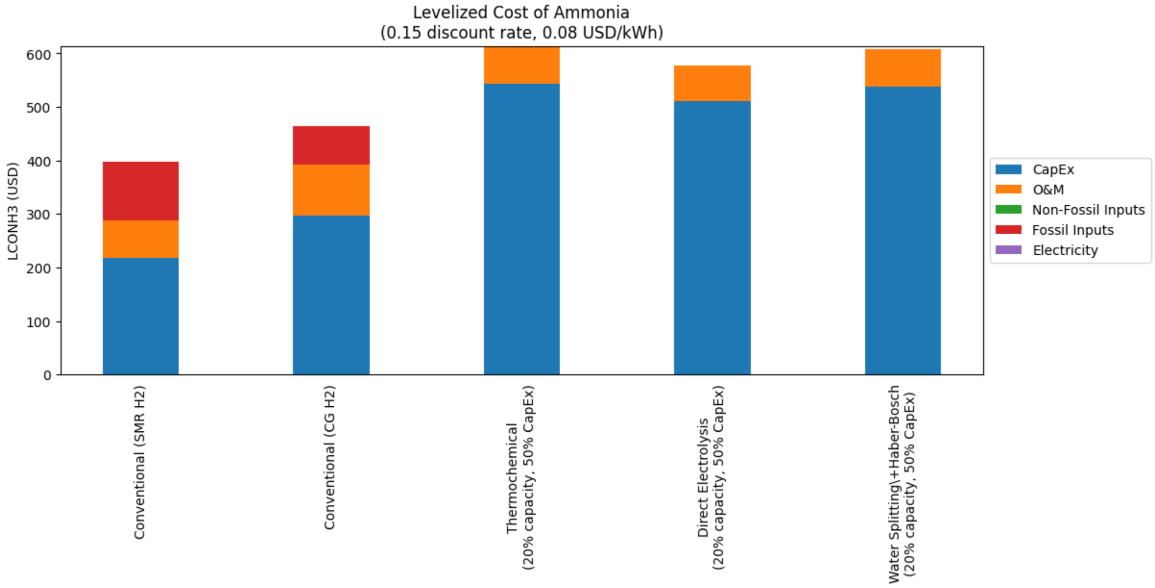
Supplemental Figure 10. Calculated Levelized Cost of Cement (50% CapEx, 20% Utilization Factor)



Supplemental Figure 11. Calculated Levelized Cost of Steel (50% CapEx, 20% Utilization Factor)



Supplemental Figure 12. Calculated Levelized Cost of Hydrogen (50% CapEx, 20% Utilization Factor)



Supplemental Figure 13. Calculated Levelized Cost of Ammonia (50% CapEx, 20% Utilization Factor)

Analysis: Why we electrify in Industry

Our analysis suggests that it will be difficult to electrify most industrial processes while maintaining cost parity. It is instructive to consider the cases of industrial processes that are currently electrified and understand why this is done. Below, we identify two attributes that are associated with electrified industrial processes.

1. The analogous thermochemical version of the reaction requires temperatures that exceed the adiabatic flame temperature of coal, gas, and oil.

For processes which are endothermic and only weakly entropically driven, such that the temperature required for the reaction to proceed at an economical rate is at or above the adiabatic flame temperature of common fuels in air (practically, >1600 °C), electricity is the most economical form of energy which can reach these very high temperatures.

However, because electricity comparatively expensive (~10X the cost of fuel at the industrial scale today; see Supplemental Figure 2), minimizing the use of electricity is typically an economic win. If carbothermal reduction (either electrothermal or electrochemical) can be used to reduce the temperature of the reaction below the adiabatic flame temperature, or minimize the potential of the reaction, it is possible it will be employed to minimize electricity consumption. Silicon production utilizes carbothermal reduction and proceeds at temperatures above the adiabatic flame temperature using an electric arc furnace. Recycling steel does not benefit from carbon as a reducing agent, but occurs at >1600 °C, again requiring the use of electricity. By contrast, metals like steel, copper or zinc utilize carbothermal reduction to bring the reaction temperatures below the adiabatic flame temperature and avoid (or diminish) the requirement of electrification.

In some cases, the temperatures required for electrothermal reduction is still too high to be economically achieved with known materials of construction, even with carbothermal reduction (>2500 °C for complete carbothermic reduction of aluminum).(*40*) Hence, this reaction utilizes electrochemical carboreduction at lower temperatures.

2. The chemical transformation is complicated and requires multiple unit operations or a catalyst and therefore electrification may be a lower cost approach because it allows for less energy, lower CapEx fewer process steps, higher purity, or product cogeneration.

For externally heated chemical reactions, resistive heating could form amore intimate contact with their reactor than a flame and therefore, electrified CapEx is often lower for space and water heating applications. Alternatively, electrification of the chlor-alkali process turns the multi-step Deacon reaction plus Solvay process or the Leblanc process into a single unit operation process. In some cases, electrification could allow for multi-step reactions to turn into single step reactions, which could save CapEx. This is often the case when the reaction is weekly exergonic at low temperatures, but endergonic at high temperatures, i.e. weakly driven by enthalpy. In this case, the lower temperature likely necessitates a thermochemical or electrochemical catalyst, however there are sufficient complexities with implementing catalysts that it makes sense to evaluate electrochemical approaches. This is the case for both the production of Cl_2 and NaOH from the obvious source (NaCl and H_2O). High purity and other secondary advantages like surface functionalization may be achieved in a more controlled way using the precision of electrical work opposed to thermal energy. In general, however, functionalization and purity problems are sufficiently complex that all methods are considered and electrochemical systems are often the most effective and least cost (this is why copper and zinc are refined using electrochemistry, because carbothermal reduction does not yield sufficient purity).

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